WORLD WEATHER

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WORLD WEATHER

Including a discussion of

THE INFLUENCE OF VARIATIONS OF SOLAR RADIATION ON THE WEATHER

and of

THE METEOROLOGY OF THE SUN

BY

HENRY HELM CLAYTON

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DEDICATION

This book is dedicated to that noble band of research workers and observers who, animated by a desire to be of service to their fellows, without hope of financial reward and with little prospect of recognition or praise, have carried on the arduous observations, reductions and discussions which have made the present treatise possible.

INTRODUCTION

The theme of this book is the weather. The difference between climate and weather as defined by an American school boy quoted by Mark Twain, is that, "climate lasts all the time, while the weather changes every day." Expressed in the more cumbersome but more exact language of science, climate is the average or normal condition of the atmosphere, while weather is made by variations from the normal.

The weather in some form or other affects every living creature. It has been the topic of universal conversation. It is the subject naturally mentioned in beginning a chat with a friend or stranger. It has been the foundation of endless jests and it has furnished a theme for countless poems. The sparkling air, the brilliant sunshine, the drifting feathery snow flakes, the pattering rain have brought joy to millions and yet the angel of death rides in the trail of the icy blast. The same wind may bring to one the intensest joy and to another the deepest tragedy. The same rain which brings tears to the eyes of a maiden robbed of an expected outing may bring smiles to an agriculturist, who sees in it the promise of an abundant crop. The same snowstorm may bring joyous anticipation of sport to a youth and may bring death to an aged neighbor. The stakes depending on the changes of the weather are so vast, that those dependent on the turns of the wheel of chance at Monte Carlo seem as nothing in the balance. But a risk dependent on the weather is not a gamble. The gambler stakes his all from choice in pursuit of excitement or gain, while the man whose welfare depends on the turn of the weather is bound by thongs of necessity. As mankind must be fed, the farmer must sow his seed and watch the turn of the weather which brings him abundance or want. The manufacturer must send his goods from regions where power is procured easily to other regions more favorable for food production, and risk their loss by the destructive hurricane. The merchant must bring his products from places where they are most readily grown to those where they are most needed, and risk their loss by moisture, heat or cold. In the United States alone more than ten thousand million dollars are taken from the soil each year. Fortunately, nature never completely deprives the

grower of needed moisture, but the total difference in value between the amount grown in a year of abundant rain and a year of deficient rain may easily be five hundred million dollars.

The toll of sickness and premature death and of losses to business from a lack of adjustment to unexpected changes of weather is so vast that it staggers all computation. It is not strange that the subject of the weather has occupied so much of the thoughts of mankind, and in the following pages an attempt will be made to explain a part of the vast stock of knowledge accumulating about the weather, especially those newer researches which indicate that the time is near at hand when weather changes can be anticipated so far in advance, as to save much of the loss and distress which now follows in the wake of the unexpected adverse conditions.

The work of the meteorologist has a spiritual as well as a material value.

In no other way has man been more haunted by degrading superstitions than in his interpretation of the signs of the sky and air.

The shining crosses formed by the sunlight in the filmly cirrus clouds, the blood-red rain, the fiery sunsets, the reverberating thunder, the blinding flashes of lightning, the pulsating aurora filled him with untold terrors; his terrible losses from prolonged droughts led him to load the air with sound by the beating of tom toms and even at times to sacrifice human victims to appease the anger of the Rain God. Through scientific research, these things have now found their natural explanation and man has learned that the universe is governed by well-regulated laws and not by angry impulse. Religion is slowly becoming elevated to the higher plane of spiritual intercourse, and is freed from the meaningless rites to appease an angry God.

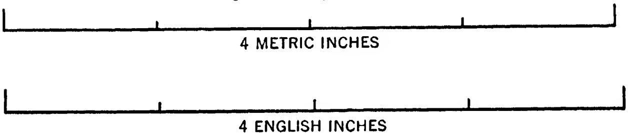
SYSTEM OF MEASUREMENT

In writing a treatise on world-wide weather changes there arises a serious difficulty from the fact that different parts of the world use different systems of measurements. Fortunately, however, the choice of units lies between the two most widely used systems, the English system and the metric system. Recognizing the desirability of uniformity of measures throughout the world, the workers in science have in large part, even in English speaking countries, adopted the metric system and much of the literature of meteorology expresses its quantities in metric units.

It seems desirable to express the measurements in this book in the system which is likely in time to come into general use, and for this reason the metric system is taken as the basis of the measurements, but as the book is written for English readers, many of whom are not familiar with metric units, the measures are made to approximate English measures of the same name. Thus 25 millimeters is called a metric inch which differs from an English inch only about 0.4 of a millimeter or 1.6%. Four metric inches equal one decimeter (one-tenth of a meter); three decimeters equal one metric foot and three metric feet equal one metric yard. Forty metric inches equal one meter.

The accompanying diagram shows how slightly the English inch differs from the metric inch. It is seen that for purposes of forming a mental picture of distances no confusion will result in considering a metric inch as equivalent to an English inch, except where great exactness is desired, in which case the inch should

Comparison of Measures.



be taken as the equivalent of 25.04 millimeters and the foot to 300.16 millimeters. Miles mentioned in the treatise are considered equivalent to 1600 meters, so that a thousand meters, or one kilometer, is five-eighths of a mile, which differs from an English mile by only a few feet (8 meters). Where both metric and English measures are given, the metric measures are to be taken as the correct measures and the English measures as approximate.

For measurements of atmospheric pressure use is made of the unit called a "bar" suggested by V. Bjerkness and adopted by the British Meteorological Office. It is the pressure of one million dynes on a square centimeter.* A dyne is defined in physics as the force required to accelerate a mass of one gram in one second one centimeter per second. A "bar" is equivalent approximately to the pressure of a column of mercury at 32 degrees F. (0° C) at 45 degrees latitude and at sea level of the length of 750 millimeters or of 29.53 inches. Four "millibars" are equiva-

* *Atmobar* would have been a better name, since *bar* is used by chemists for the pressure of one dyne per square centimeter.

lent to three millimeters, a "millibar" being one-thousandth part of a "bar."

For persons accustomed to other scales the following comparison of scales will serve to give a mental picture of the different scales.

Millibars	*Millimeters*	*Inches*
1000	750	29.53
1004	753	29.65
1008	756	29.77
1012	759	29.88
1016	762	30.00
1020	765	30.12

For measurements of temperature both the Fahrenheit and the Centigrade scale are used, although both are considered unsatisfactory. It is hoped that an agreement may soon be reached by meteorologists as to the best temperature scale for general use.

ACKNOWLEDGMENTS

I am indebted to G. O. Wiggin, Chief of the Argentine weather service and to my associates A. Rankin, William Hoxmark, Nils Hessling, Robert C. Mossman and A. Galmarini for assistance in the preparation of the material for this book, to Dr. C. G. Abbot, Dr. H. Shapley, and Prof. Arthur G. Webster for reading and correcting certain parts of the manuscript, and especially to Prof. W. M. Davis and Dr. C. F. Brooks for reading a large part of the manuscript and suggesting many minor modifications of the text. Also to my wife and daughter for assistance in the preparation of the manuscript.

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CHAPTER I

THE FORCES CONTROLLING WEATHER CHANGES

SUMMARY

In order to illustrate the effect of heating any part of the atmosphere, the familiar example of a stove heating the air of a room is introduced to show that the heating of any body of air to a temperature higher than the surrounding air will cause air movement.

Examples are given of the heating of air over land surfaces, warmed by the sun and the resulting air movement in the cases of sea breezes, mountain breezes and monsoons. On the other hand, examples are cited of winds caused by the cooling of air over land or water surfaces to a point cooler than the surrounding land or water, as in the case of land breezes, of air flowing out of valleys by night and of winds from glaciated surfaces.

The fact is pointed out that such movements are associated with differences in atmospheric pressure, more especially in the case of the large atmospheric exchange between ocean and continent. In other cases, the differences of pressure are so small as not easily to be measured.

The many modifying conditions are explained which in the free air affect the interchange of air between regions of different temperature. Among these modifying conditions are:

(1) The decreasing density of the air with increasing height above the ground, by virtue of which the air cools in rising.

(2) The effect of the changing state of the moisture in the air, as a result of which atmospheric conditions are altered.

(3) The influence of the earth's rotation which deflects the moving air and generates cyclones and anticyclones.

The general circulation of the air and its causes are considered and schematic representations are given of the atmospheric circulation as developed by Maury, Thompson, Ferrel and Bjerkness. Owing to lack of sufficient observations, none of these theories of the general circulation can be submitted to crucial tests. Much space is given to the views of Ferrel which seem to the author most in accord with observed conditions.

INTRODUCTION

Of the many mysterious forces controlling the course of natural phenomena, gravity, electricity, magnetism, heat and light, almost all have been called upon at some time or other to explain the weather. Since the moon, by the force of gravity, raises tides in the ocean, many persons have thought that the force of gravity acting from the moon might be the principal cause of weather changes, and there are to-day hundreds of intelligent people who

still believe in this action as a possible, if not a probable, factor in the control of weather. Most of these people believe that no adequate attention has been paid to this theory; but, as a matter of fact, an enormous amount of work has been done by numerous workers to discover facts to test the theory, and a very slight tide has been found in the atmosphere due to the daily rotation of the earth beneath the moon: but it is so slight, that thousands of the most delicate observations have been required to prove it. It is probable that there is also a very slight monthly tide due to the movements of the moon around the earth, but, up to the present time, there has been no adequate proof of it. The moon theory has held its place, however, and continues to fascinate many workers, perhaps because there are weather changes of a periodic or semiperiodic nature which are very near the length of the period between the same phase of the moon and fractions of it, as a quarter or a third. As will be shown later these changes are probably connected with the period of the solar rotation which happens to be very near that of the lunar period. The heat coming from the moon has also been shown to be insignificant. Measured by the most delicate instruments known to science, it is found to be less than one millionth part of the heat received from the sun.

When electricity and magnetism were little understood, these also were frequently called upon as the fundamental causes of meteorological changes and at least one author has maintained that "Electricity is the ultimate cause of all physical phenomena." But the principles established by laboratory experiments do not permit these forms of energy as ordinarily manifested to be considered as fundamental. The one form of energy that experiment and experience show to be adequate to cause atmosphere disturbances is heat, and the universal opinion among meteorologists who have given much thought to the subject, is that the heat derived from solar radiation is the main factor. The heat from all other sources, the interior of the earth, the moon or the stars is insignificant in comparison and incapable of producing weather changes. Gravity, electricity, magnetism, and light, each play a part in causing weather changes, but these serve only to modify the all-pervading action of the solar heat.

The action of electricity is seen in the thunderstorm and electricity is perhaps one of the forces modifying precipitation. Light changes the chemical state of the air by liberating ozone and this causes changes in the absorption and radiation of heat. The modifying influence of magnetism and other similar

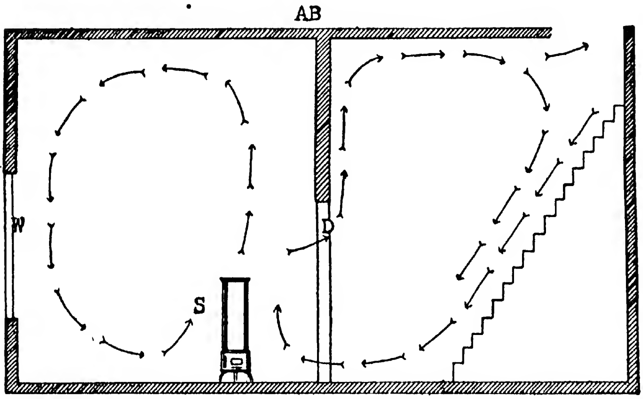
forms of energy are less secure. Certain local winds have been attributed to the rise and fall of the tide and it is possible that solar heat changes are brought about by tidal action on the sun.

THE MOTIONS OF THE AIR UNDER THE INFLUENCE OF HEAT

Beginning then with the familiar action of heat on the air in a living room, an endeavor will be made to follow its action in the complex movements of the atmosphere.

If in Fig. 1 *AB* represents the interior of a house in which

FIG. 1



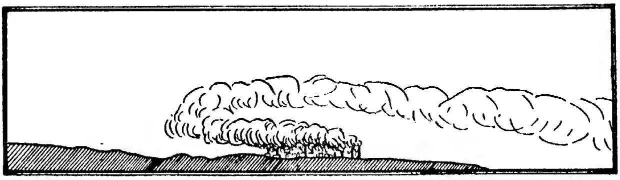
Circulation of Air in a Room Heated by a Stove

there are a stove *S*, a window *W*, and a door *D*, then, when the stove is heated the air about it is heated, expands and becomes lighter per unit volume and is lifted upward by the pressure of the cooler, and therefore denser and heavier air around and beneath it. As the cooler air near the stove in turn becomes heated a current is formed which extends vertically to the ceiling, passes across to the opposing wall, descends and passes across the floor to the stove *S*, where it again joins the ascending column. These movements can be easily followed if a bit of smoke is inserted into the moving air. With a delicate thermometer it can be ascertained that the air cools as it descends along the opposite wall and passes across the floor. The cooling is especially rapid near the window and there it will be found, that the descending current is greatly accelerated as compared with the air in contact with the wall on either side. Also, if

there is a flight of stairs in the room, the air will be flowing down these in a series of aërial cataracts. If the door of the room be open, it can be ascertained that the air is passing out at the upper part of the door, while cooler air is flowing in below. It will be noted also that the air flowing out of the door occupies more than half of the space of the door. The mass of air moving into and out of the room must be equal; hence, the difference in volume, shown by the greater vertical thickness of the warmer portion, is a measure of the expansion by heating.

In a hilly country moving air currents due to local differences of temperature can be felt on clear nights after sunset flowing out of ravines across a road or into more open country. The hills become cooled by radiating their heat into space, and the

FIG. 2



Drift of Smoke Showing Movement of Air in a Sea-breeze

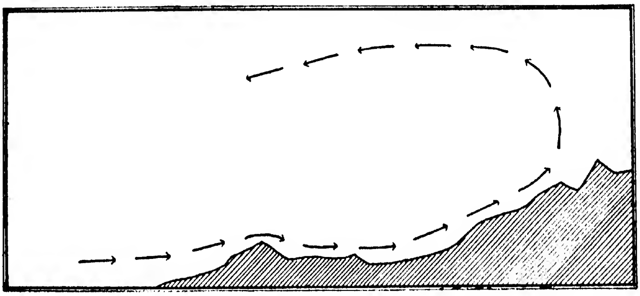
air in contact with the sides of the hills flows down to lower levels.

Currents due also to local differences of temperature can be seen on clear days, when no storm disturbs the atmosphere, where a stretch of land lies near a surface of cooler water, and especially if the land rises steeply upward so as to catch the sun's rays at a right angle at some time in the day. The winds arising from these causes are called *sea breezes*. The surface of the land absorbs the rays of the sun and becomes heated, while these rays heat the water but little, first, because about half is reflected; second, because the rays penetrate to a considerable depth in the water and are diffused through a larger mass of matter than on the land; third, water has a high specific heat, so that the solar energy does not cause a marked rise of temperature; and fourth, a part of the heat is used up in evaporation from the water surface. The land acts like the hot stove in the diagram and sets up a similar circulation. The air in contact with the heated land surface is warmed and expands. Each unit part of it becoming lighter than a similar volume of air over the water

is lifted upward by the inward pressure of the cooler air, thus starting a current which continues to grow in strength as the solar heat increases with increasing height of the sun above the horizon.

In the case of cities near the seacoast, the whole process can be followed by means of the drifting smoke coming from the factory chimneys. From Blue Hill on quiet summer days I have frequently followed the progress of the sea breeze over Boston ten miles to the north. The sea breeze begins off shore about nine in the morning as a gentle wind from the east or northeast and, as the sun approaches the zenith and its radiation becomes more in-

Fig. 3



Sea-breeze of Peru and Northern Chile

tense because of its coming through less air and at a more direct angle, the breeze increases in intensity and penetrates on to the land. By two or three in the afternoon, it has shifted more to the southeast and greatly increased in intensity, but gradually dies away by evening. As seen from the hill the smoke has the form shown in Fig. 2.

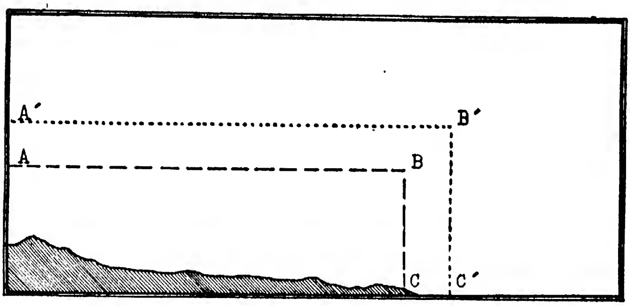
As the air passes back over the land, it gradually warms and finally, being heated by contact with the land, becomes an ascending current like that over the stove. Passing back over the cool current it is carried out to sea and downward to some extent to replace in part the cool air moving under the influence of gravity toward the land. When the land slopes upward from the seacoast, as illustrated in Fig. 3, the sea breeze is greatly strengthened, except when the slant is away from the position of the sun at noon. If the slant is at an angle to get the rays of the early afternoon sun nearly at right angles, as it is at many places on the west coast of America, the strength of the sea breeze is greatly increased. Fig. 3 illustrates the position of the land

and sea on the coast of Peru and northern Chile, where the contrast between land and water is further strengthened by the fact that a cold current of water flows northward along the coast, and by the fact that the land is a desert, so that the heating of the land surface is not tempered by vegetation or the evaporation of water and becomes a veritable stove.

Bowman,[1] writing of the sea breeze in this region, says:

"Everywhere along the coast the *virazon,* as the sea breeze is called in contradistinction to the *terral* or land breeze, enters deeply into the affairs of human life. According to its strength it aids or hinders shipping; sailing boats may enter port on it or it may be so violent, as, for example, it commonly is at Pisco,

FIG. 4



Expansion of Air causing Sea-breeze

that cargo cannot be loaded or unloaded during the afternoon. On the nitrate pampa of northern Chile (20° to 25° S.) it not infrequently breaks with a roar that heralds its coming an hour in advance. In the Majes valley (12° S.) it blows gustily for half an hour and about noon (often by eleven o'clock) it settles down to an uncomfortable gale. For an hour or two before the sea breeze begins the air is hot and stifling, and dust clouds hover about the traveler. The maximum temperature is attained at this time and not around 2 P. M. as is normally the case. Yet so boisterous is the noon wind that the laborers time their siesta by it, and not by the high temperature of earlier hours. In the afternoon it settles down into a steady, comfortable, and dustless wind, and by nightfall the air is once more calm."

The fact that the sea breeze begins over the sea at a distance from the land arises from the fact that the air over the heated

[1] Bowman, Isaiah—*The Andes of Southern Peru,* pp. 130–131. New York, 1916.

land expands both laterally and vertically. In Fig. 4, let A, B, C represent a section of air before sunrise. Under the influence of the sun's rays, the land and the air immediately over the land become heated and the air being a gas expands both laterally and vertically, so that the dividing line A', B', C', between the warmed air and the unwarmed sea air is not at the coast line, but off the coast where the sea breeze begins. This lateral expansion of the air plays an important part in many meterological phenomena, as will be seen later. On the other hand, at night, when radiation from land is much more active than from water, the air over the

Fig. 5

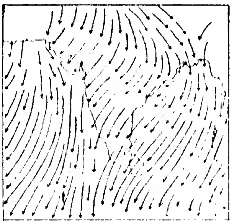


Fig. 6

(From the Atlas of the Indian Ocean of the German Naval Observatory.)

Winter

Summer

Monsoon Winds of India

land becomes colder than that over the water and the motion is reversed, the surface air flows from the land to the water, but these winds are never so strong as the sea breezes.

Akin to the sea and land breezes are the mountain and valley winds. The heated side of the mountain sets in motion a stream of air moving upward during the day, while at night the air chilled by contact with the mountainside flows down into the valley again.

As the contrast between day and night calls forth local sea and land breezes, so the contrast between winter and summer calls forth movements on a vastly larger scale. The land surfaces are much more heated in summer, when the sun is nearly vertical, than in winter, when it is nearer the horizon, and, in those parts of the world where the motions of the atmosphere are not greatly interrupted by storms, a notable feature of the climate is the inward movement of the air from the ocean to the continent

during the summer and the outward motion in the winter. These alternating winds are called "monsoons" in India, and are illustrated in Figs. 5 and 6. As pointed out by Simpson,[2] these winds are not due merely to the heating and cooling of the land surfaces of India, but to the heating and cooling of the vast land surfaces of Asia of which India is a part.

Ward[3] has shown that, if the prevailing winds of July and January are plotted, the same system of alternating winds is visible in the United States. Toward the heated plains of the western United States and Canada a vast stream of air is directed in midsummer from the Gulf of Mexico and from the Pacific Ocean, while during midwinter there is a vast flow of air from the cold plains of Canada southward across the United States to the Gulf and to Mexico (see Figs. 7 and 8).

FIG. 7

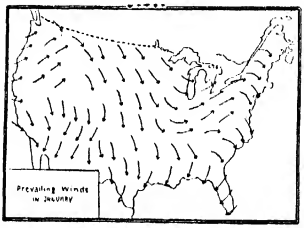
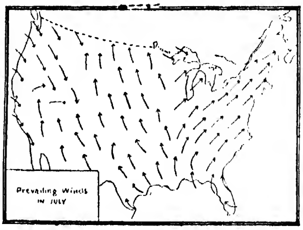


FIG. 8



Monsoon or Seasonal Winds of the United States—After Ward

The warm water poured into the north Atlantic Ocean by the Gulf Stream and the Antilles Current strongly accentuates the normal winter difference between the temperature of the water and the land in high latitudes. The warm ocean water acts on the air like the radiator in a house heated by hot water or steam and takes the place of the stove illustrated in Fig. 1.

Sandstróm[4] analyzed the air movements of Europe for January, 1913, and showed that there was an outward flow of the cold air from the continent toward the warm surface waters of the north Atlantic (see Fig. 9), just as the cold air from the sides of a room flow toward a stove or a steam radiator.

Ward's diagram, Fig. 7, shows that there is a strong flow into

[2] Simpson, G. C.—"The South-West Monsoon," *Quarterly Jour. of the Royal Meteor. Soc.*, pp. 151–172. London, July, 1921, Vol. 47.

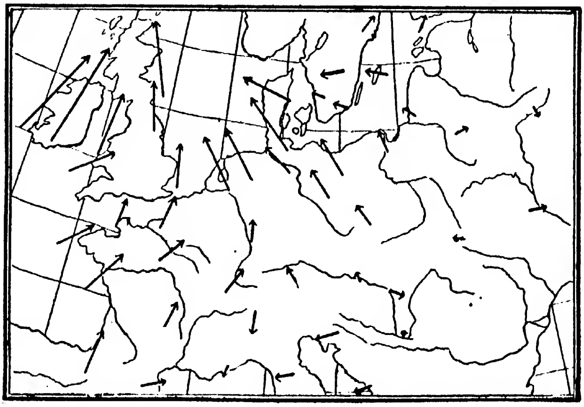
[3] Ward, Robert DeC.—"The Prevailing Winds of the United States," *Annals of the Association of American Geographers*, Vol. 6, pp. 99–119; also *Monthly Weather Review*, p. 576. Washington, Aug. 1919.

[4] Sandstróm, J. W.—"Working Up Wind Observations," *Monthly Weather Review*, p. 547. Washington, Nov. 1915.

the Atlantic from the American continent on that side of the ocean.

Notwithstanding the many similarities between the movements of the air in a room and the general movements of the atmosphere under the influence of heat and cold, there are also marked differences, owing to the fact that the air in a room moves such short distances that the modifying influences do not become noticeable. In order to understand atmospheric processes, as seen on a world scale, it is necessary to consider these modifying conditions.

Fig. 9



Mean Winds Over Europe, January, 1913—After Sandström

MODIFYING EFFECT OF THE DECREASE OF DENSITY WITH HEIGHT

The decreasing density of the atmosphere with increasing height is one of the causes which greatly modify atmospheric changes. The atmosphere is composed of a mixture of gases, of which oxygen, nitrogen and water vapor form the principal part, with a small admixture of carbon dioxide, hydrogen and traces of other less known gases. According to the conception of physicists, these gases are formed of separate molecules moving with great velocities and continually colliding and rebounding. Each little molecule is acted on by the force of gravity and the total weight or pressure of the air at any point is determined by the number of molecules above that point. As the number diminishes with increased height above the earth's surface, the atmospheric

gases under diminished pressure expand and in expanding cool. The heating of air by compression, or cooling by expansion, is a well-known process and is much used in the arts. Most people are familiar with the heating of the air by compression in a bicycle pump and the cooling by expansion of the air or other gas by means of which artificial ice is formed. The decrease of the pressure of the air follows, approximately, a very simple law, and would follow it exactly, if it were not for the modifying influence of changing temperature, moisture, etc. For every 3.1 miles (5 km.) of ascent above the earth's surface the pressure of the air diminishes one half, so that at 3.1 miles (5 km.) one half of the atmosphere remains, at 6.2 miles (10 km.) one quarter, at 9.4 miles (15 km.) one eighth, at 12.5 miles (20 km.) one sixteenth, and so on.

At first the amount of air decreases very rapidly, and afterward more and more slowly, until at very great heights there is scarcely any perceptible change, and the atmosphere fades off into space as imperceptibly as night fades into day. The conception of Chamberlin [5] and Moulton is that the molecules of air move in larger orbits between collisions, until finally collisions become very rare, and the particles rebounding from each other move out into space in large orbits, the motion being slowly retarded by the attraction of gravity, until the molecule turns in its track and approaches the earth again. Under favorable conditions it may even become a little satellite of the earth, like a microscopic planet.

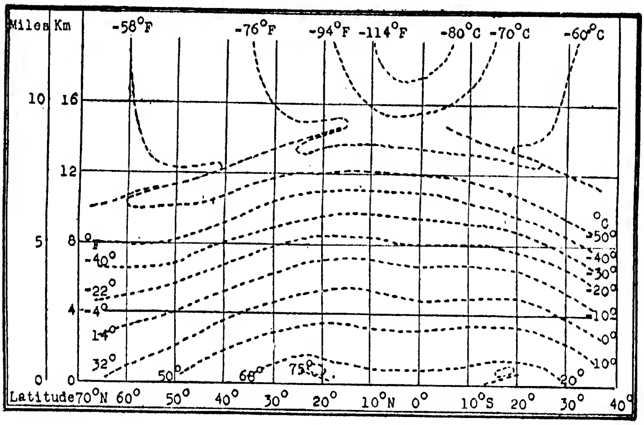
A body of air heated by contact with the ground occupies more space and becomes relatively lighter than the air around it and is pressed upward. As it rises it expands and grows colder at the rate of 1.6° F. per 300 metric feet or 1.0° C. for each 102 meters of ascent. The rate is diminished somewhat if there is moisture in the air and also is changed somewhat at great altitudes. This rate of cooling is called the *adiabatic* rate. If there were no vertical currents of air the atmosphere would absorb solar radiation and approximate to a uniform temperature at least in the lower layers. If, on the other hand, there were no absorption of solar heat and the air were cooled only by ascending currents, the temperature would decrease at the *adiabatic* rate from the bottom to the top of the atmosphere and the upper layers would be very cold. The actual rate of cooling, at least up to about six miles, in the Arctic Circle rising to nine miles at the tropics,

[5] Chamberlin, T. C.—*The Origin of the Earth*, pp. 23–24. Chicago, 1916.

is at a rate of about 2.7° F. per thousand feet in the lower air increasing to 4.5° F. per thousand feet in the region between three and seven miles. Above the height of six miles near the Arctic Circle, increasing gradually to a height of nine miles near the tropics, there appear to be no ascending currents and, because of this lack of vertical circulation, there comes a marked change in the distribution of temperature above and below this boundary.

Fig. 10 gives a plot of the isotherms at different heights up to

FIG. 10



Temperatures at Different Heights—Year

12.5 miles (20 km.) between 70° N. and 40° S. The results are based chiefly on the Franco-Swedish exploration in northern Scandinavia near latitude 68°, the observations in central England, the observations of the Teisserenc de Bort and Rotch expedition in the Atlantic between 40° N. and 8° S., the German expedition to Lake Victoria Nyanza in central Africa, and the observations carried out by Griffith Taylor for the Australian Weather Service. In the case of the results obtained by the kites and sounding balloons of the Atlantic, they were grouped about the latitudes 0°, 10°, 20°, 30°, and 40°, and means were obtained for each group. It is thus seen, that the plot represents a section in the northern hemisphere over the Atlantic Ocean and western Europe.

The isotherms for 38° latitude are a few hundred meters higher than those found over St. Louis from observations by the staff

of the Blue Hill Observatory, but they would not be greatly changed if the observations over the whole world were included. In the southern hemisphere, for lack of observations between 10° and 30° S., the isotherms are provisional.

This diagram brings out clearly five salient facts shown by the investigations of the upper air: (1) a region called the *troposphere* between the earth's surface and 6 to 9 miles above it in which the temperature decreases rapidly with increasing height, so that the isotherms lie over each other, with a gradual slope upward toward the equator; (2) a region called the *stratosphere,* where there is very little change of temperature with increase of height, so that the isotherms are nearly vertical; (3) a boundary line, where there is a marked rise of temperature for a short distance in a vertical direction which slopes downward from the tropics, where it has a height of about 9 miles, to the Arctic Circle, where it has a height in the northern hemisphere of about 6 miles; (4) the air is colder in the polar region and warmer at the equator up to a height of 5 or 6 miles; (5) above 6 miles the air is coldest above the equator and warmest above the polar region.

The warmth near the earth's surface in the equatorial zone, no doubt, finds an explanation in the greater absorption of solar radiation in that region where the sun is most nearly overhead at midday; while the cold of the upper air probably finds its explanation in the expansion of ascending air which reaches great heights in the equatorial region, and, then descending toward the pole, warms by compression. If air at 120° F. below zero (—84° C.) which is the lowest temperature observed above the Atlantic on the equator, were to move toward the pole and descend parallel to the boundary of the *stratosphere,* indicated by the broken line in Fig. 10, it would descend about 4 miles and warm up about 110° F. by compression; but as the observed air temperature is about —50° F. instead of —10° F., it must lose about 40° F. by radiation to space, if the hypothesis assumed above be the true explanation of the warmth in the polar region. Other minor features brought out by the diagram, are a permanent inversion of temperature between 20° and 25° latitude in the northern hemisphere and a maximum of temperature at those latitudes up to five miles, after which the temperature falls rapidly, and the maximum of temperature at higher levels is found about 10° N. Probably similar conditions exist near 20° S., although the data are as yet lacking to prove it. It is also probable that the air is colder throughout the *troposphere* in the

southern hemisphere than in the northern, but more observations are necessary to render this secure.

Humphreys, Gold and Emden have offered a different explanation of the *troposphere* and *stratosphere* from the standpoint of the meteorological physicist. A condensed explanation of this view given by Humphreys[6] is as follows:

"But since the coefficient of absorption of the air [for radiant energy], as of other objects, changes but little, if at all, with temperature, while its emissive power decreases rapidly as it grows colder, and since the intensity of the incident terrestrial (including atmospheric) radiation remains roughly constant up to an altitude of many kilometers beyond the first 4 or 5, it follows that the upper limit of the convective region is not, as formerly supposed, the outermost limit of the atmosphere, but at that elevation at which the temperature is so low that the loss of heat by radiation is no longer in excess of, but now equal to, its gain by absorption. Beyond this level temperature does not decrease, or does so but slightly, with increase of elevation; nor would it so decrease, at least at nothing like the present rate, beyond any level, however low, at which absorption and radiation became equal.

"In short, then, the air grows colder with elevation because, (1) owing to its transparency to solar radiation it is heated mainly at the surface of the earth, and (2) because at ordinary temperatures it emits more radiation than it absorbs. These together so affect the density of the atmosphere as to induce vertical convections, and thereby to establish and maintain throughout the region in which they are active, a rapid decrease of temperature with increase of elevation. . . .

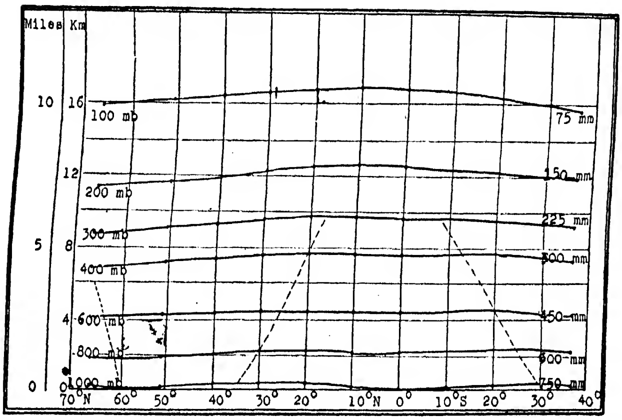
"If, then, as is approximately true, the temperature does not decrease with increase of altitude above 11 kilometers, it follows that this must be the limit of anything like a marked vertical convection and from this in turn it follows, since conduction is negligible, that the upper atmosphere must be warmed almost wholly by absorption of radiation in part solar and in part terrestrial; but exactly how much of the final temperature of the upper atmosphere is due to the one source of heat and how much to the other it is not possible to say. . . . It would appear that the temperature of the isothermal region must be due chiefly to absorption of long wave-length radiation given off by the water vapor and other constituents of the atmosphere at lower levels, and to only a very minor degree to the absorption of solar radiation."

[6] Humphreys, W. J.—*Physics of the Air*, pp. 42 and 45. Philadelphia, 1920.

The conditions described by Humphreys probably play a part in the physics of the atmosphere, but the theory fails to explain the intense cold found at great heights above the equator and the steady increase of temperature toward the pole in the *stratosphere*.

From the mean temperature of the air column it is possible to compute the height at which any particular pressure will be found, and this was done for pressures of 100, of 200, of 300, etc., millibars down to 1000 millibars at sea level, 100 millibars being

FIG. 11



Pressure at Different Heights—Year

approximately equal to 3 inches or to 75 millimeters. The results are shown in Fig. 11.

At the bottom of the atmosphere, a high pressure is found at the latitude of 36° N. and 30° S., but at successively higher levels this maximum is found nearer and nearer the equator, until at the height of between seven and eight miles the maximum is about 10° north or else between the equator and 10° N. As will be shown later, the air probably wells up at the equator and above ten miles slides slowly down these pressure slopes toward the poles, the poleward component of motion being retarded by the development of an immense atmospheric whirl near the poles, the centrifugal force of which lowers the pressure and determines the backward movement of the air toward the equator at a lower level. The broken lines in Fig. 11 show the backward slope of the position of maximum pressure toward the equator with in-

creasing height above the earth's surface. Near the latitude of 5° N. there is found at the earth's surface a minimum of pressure which gradually fills up with increasing height above sea level and flattens out at a height of about seven miles, owing to the effect of the slower decrease of temperature with height in that region.

At 65° there is another minimum of pressure which is found nearer the pole at higher levels and probably finally reaches the poles at no great height. The displacement of this minimum toward the pole with increase of altitude is shown by the broken line.

MODIFYING EFFECT OF MOISTURE IN THE AIR

Another factor of great importance in modifying the influence of solar heat on the atmosphere is the presence of water vapor in the air. Water vapor differs from all the other gases composing the atmosphere, in that it is condensed into a liquid within the observed ranges of temperature.

Molecules of water are continually leaving and entering every water surface. When the number leaving exceeds the number entering, the water diminishes in amount and is said to evaporate. Energy is used up in the process and the result is a lower temperature, so that evaporation is one of the processes causing a lower temperature of the air. When more molecules of water vapor enter a water surface than leave it, the result is condensation and a liberation of the heat energy taken up in the process of evaporation. The number of molecules which can remain in the form of vapor depends on the temperature. At each temperature there is a given quantity per unit volume that can remain in the form of gas. If the number exceeds this definite quantity, condensation takes place, and if it is less, evaporation occurs. When a unit volume of air includes the maximum amount of water vapor which it can include before condensation begins, it is said to be saturated. This condition varies with the temperature. At a high temperature a unit volume of air may include many more molecules of vapor than at a low temperature. Hence, at high temperatures the air usually includes a much greater quantity of water vapor than at low temperatures. The quantity of vapor in the air at any time is referred to as the absolute humidity and can be measured by the pressure exerted by the water gas, by the number of grams it would weigh if condensed into water, or by the depth of the condensed water on a unit surface.

Another way of expressing the humidities is by the percentages of vapor necessary to saturate the air at any given temperature. When a given space is saturated, so that the vapor begins to condense into water, the humidity is 100 per cent. If only half that amount of vapor is present, the humidity is 50 per cent, and if one third, it is 33 per cent, etc. This is called the "relative" humidity and does not give an idea of the absolute amount of vapor unless the temperature is taken in account. At very low temperatures, saturation occurs with a very small amount of actual water, while at a high temperature a given space when only 30 per cent saturated may hold a great deal of actual water vapor. Hence, it follows, that, by lowering the temperature of warm air, the relative humidity increases and may reach the point of saturation, so that the water vapor begins to condense.

It has been explained in preceding paragraphs that air in rising comes under less pressure and expands and that in expanding it cools. On account of the cooling, the relative humidity increases and may reach the point of saturation, so that the contained moisture begins to condense into water. In condensation molecular energy of the vapor (latent heat) is used up in decreasing the rate of cooling of the air as it rises. The amount of energy liberated depends on the number of vapor molecules of water vapor present and hence on the temperature. In dry air the rate of cooling is 5.35° F. for 1000 metric feet of ascent; but in saturated air at ordinary temperatures, it is only about half this amount, and in warm saturated air is only about 2.0° F. for 1000 metric feet. For this reason, when water vapor begins to condense into cloud and rain, the ascending current of air may rise to very great heights before it comes into equilibrium by reaching air of its own density. This is undoubtedly the case in thunderstorms. On the other hand, when the air whose cooling has been retarded by the condensation of moisture begins to descend, it warms up, the condensed moisture evaporates and thereafter the warming of the air proceeds at the rate of 5.35° F. for 1000 metric feet; so that, when it descends to the earth, as it sometimes does on the lee side of a mountain, the temperature is high. Owing to the first cause, water vapor tends to intensify ascending currents of air, and to the second, tends to retard their formation by replacing the cold air with warmer dry air, thus restoring the equilibrium previously upset by differences of temperature. Also, when water vapor is condensed and falls as rain, the air is made lighter to the extent of the weight of the water condensed and falling to the earth as

rain. The condensation of the water vapor, however, causes a change in the composition of the air, diminishing the amount of water vapor and leaving a larger proportion of oxygen and nitrogen, thus increasing the density of the air. According to Humphreys: [7]

"On very warm days water vapor may amount to five per cent or more of the total gas molecules present, and the air, therefore, be roughly two per cent lighter than it would be if perfectly dry. Of course, changes from saturation to utter dryness, or the reverse, do not occur in nature, but a variation of as much as 50 per cent in the absolute humidity at a given place does occur through evaporation, condensation and air movement. Hence, on very hot days a change of one per cent in the weight per unit volume of the lower air as a result of altered composition alone is quite possible and indeed often occurs. This produces a difference in buoyancy of the same order as that caused by a 3° C. change in temperature and therefore may be decidedly important."

Sir Oliver Lodge estimates the amount of energy that may be available from that source at nearly a thousand million foot-tons per acre.[8] Falling rain, however, tends to drag the air down with it and thus to counteract any excess of buoyancy that may arise from condensation of water vapor. Under the thunderstorm an actual descent of air is caused by the falling rain.

Another important way in which water vapor affects the heat process of the air is that as a vapor, or gas, it absorbs solar radiation and when condensed into clouds it reflects as well as absorbs, so that under dense clouds only a small part of the sun's radiation reaches the earth. As is shown in the subsequent chapter on solar radiation, nearly half the sun's heat is absorbed by a cloudless sky in tropical regions where the humidity is high. Dr. Abbot [9] and his associates have shown that more than 70 per cent of the direct rays of the sun are reflected by a cloud surface and a large part of the remainder are absorbed, so that under a canopy of dense clouds only a small part of the sun's radiant energy reaches the earth's surface. As will be shown later, the direct absorption of the sun's radiant energy by moist air pro-

[7] Humphreys, W. J.—*Physics of the Air*, pp. 95–96. Philadelphia, 1920.
[8] Lodge, Sir Oliver—*Nature*, p. 407. November 25, 1920.
[9] Abbot, C. G., Fowle, F. E., Jr.—*Annals of the Astrophysical Observatory of the Smithsonian Institution*, Vol. II, p. 162. Aldrich, L. B.—*Smithsonian Miscellaneous Collections*, Vol. 69, No. 10, Washington, 1919; also *Monthly Weather Review*, p. 154, Mar. 1919.

duces a series of weather conditions which are very distinct from those arising from absorption of solar radiation by the land and water surfaces of the globe.

MODIFYING EFFECTS OF OCEAN CURRENTS

The waters of the ocean do not heat rapidly under the influence of solar radiation, but there is an accumulation of heat until incoming and outgoing radiation balance. The water differs from the land, moreover, in the fact that the water moves from one part of the globe to the other, carrying its temperature with it. In the surface of the ocean there are well-defined and persistent currents, carrying the warmth of the tropics northward in one region and bringing the cold polar waters southward in another. The best known of these currents is the Gulf Stream. Maury [10] says of it: "There is a river in the sea; in the severest droughts it never fails and in the mightiest floods it never overflows."

The counterpart of this warm current in the Atlantic is a cold return current along the coast of Spain and near the island of Madeira carrying the cold water of the northern oceans southward. There is also a cold current from the Arctic near the east coast of Greenland bringing the Arctic waters southward. Moreover, there is an underflow of cold water toward the equator, which in part compensates for the flow of the warm surface water toward the pole. Currents similar to the Gulf Stream are found on the east coasts of Asia, Africa and South America, while cold currents are found on the west coast of North and South America and along the west coast of Africa. The drift of the ocean in different regions is seen outlined in Fig. 12, in which the points of the arrows show the direction toward which the waters are moving. Fig. 13 shows the part of the ocean where the temperature is above 80° F. (26.7° C.) shaded by continuous lines and the part where the temperature is below 50° F. (10° C.) shaded by broken lines. It is seen that the warmest waters of the world are in the Indian Ocean and the tropical Pacific west of 140° W. and also in a region which extends from the coast of Africa along the northern coast of South America. Both of these regions are regions of low pressure, high humidity and heavy rainfall. Fig. 14 shows how the temperature of the water differs from the mean of the latitude in which it is found and the differences are referred to as latitude anormals. The warmer waters are shaded with continuous lines

[10] Maury, M. F.—*Physical Geography of the Sea and Its Meteorology*, London, 1860, p. 25.

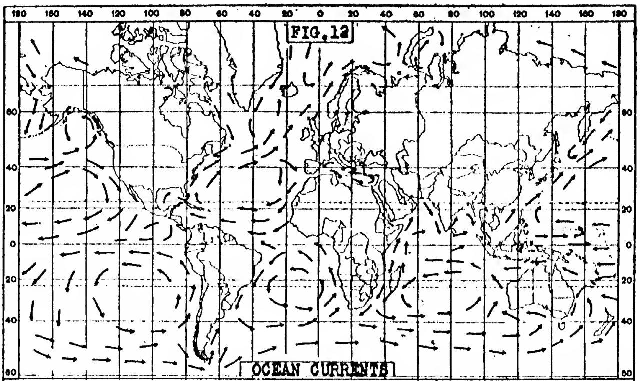


FIG.12
OCEAN CURRENTS

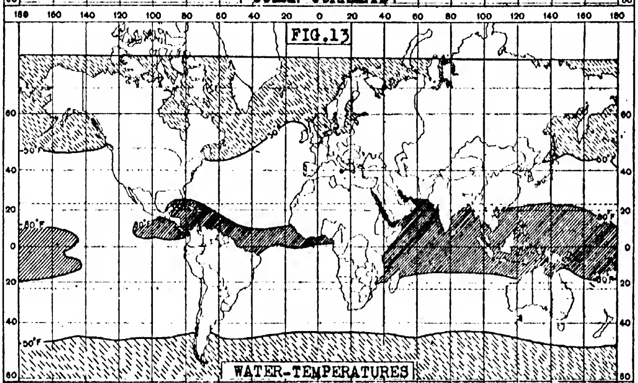


FIG.13
WATER-TEMPERATURES
80°F
50°F

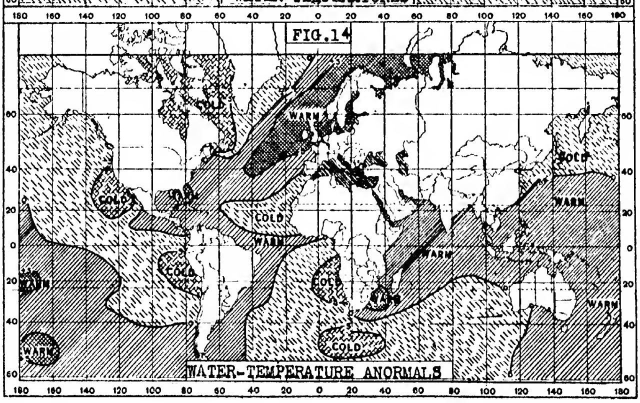
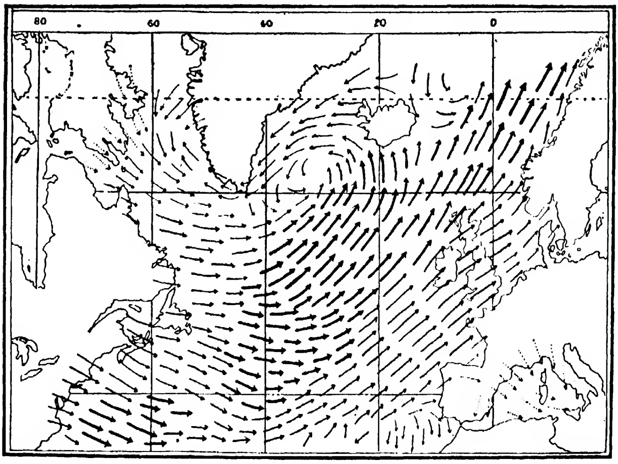


FIG.14
WATER-TEMPERATURE ANORMALS
WARM
COLD

crossed where the excess over normal for the latitude is 5° F. or more; and the colder waters are shaded with broken lines, crossed where the deficiency is 5° F. or more.

The map shows that the largest areas of cold water for the latitude are in a belt to the west of the Americas and to the south of Africa, while the warmest are in the north Atlantic and in the region extending from the east coast of Africa to the middle of the Pacific and southward to 60° latitude. These differences of temperature exert an important influence on the wind and weather of the world. The temperature of the northern oceans is

FIG. 15



Winds Over the North Atlantic, January and February, Showing Cyclonic Circulation. From data of *German Naval Observatory*

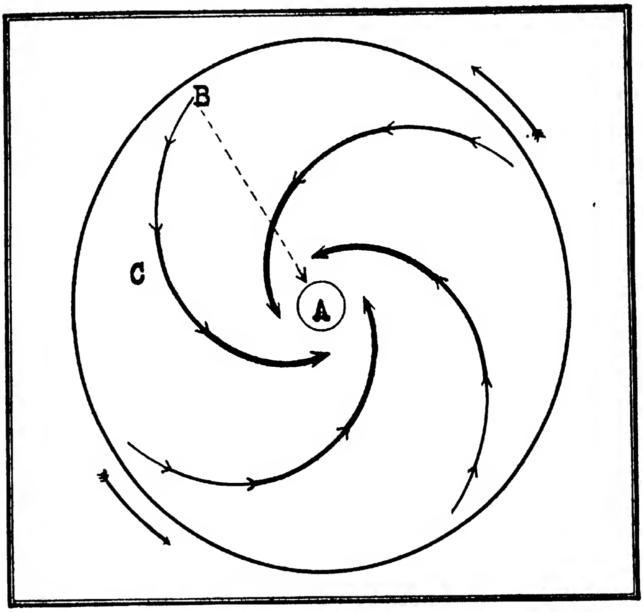
especially high as compared with the continents in the same latitudes. This fact explains the circulation of winds setting into these regions from all sides as illustrated in Fig. 15, showing the wind circulation in the north Atlantic for January.

MODIFYING EFFECT OF THE ROTATION OF THE EARTH

The rotation of the earth deflects air movements from straight lines and profoundly modifies the results of these movements. One of the easiest ways of studying the movements of a fluid in rotation is in a bowl of water in which water is flowing out at

the bottom. If a bowl, like the circular basin shown in Fig. 16, be filled with water, and the water be allowed to flow out at the bottom at a point *A*, the water will flow in a straight line *BA* toward the center, provided the water has no motion when *A* is opened. But, if the bowl or the water is put in rotation, as indicated by the arrows, the water will no longer move in straight

Fig. 16

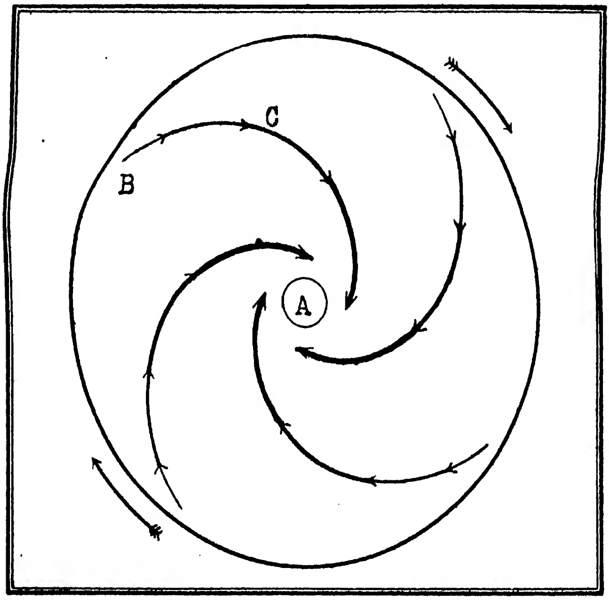


lines, but in curves, *BCA*, with an accelerated speed as it approaches the center. In this way, a violent whirl is developed around and near the central point, *A*, so that a centrifugal trend is generated so great that all the water is carried away from the immediate center leaving a small opening without water. This phenomenon also develops in the atmosphere in the case of violent whirls, and has been called "the eye of the storm," although in this case there is not a vacuum, but only a greatly decreased pressure resulting from the diminished quantity of air. If the bowl or the water is rotated in the opposite direction, the rotation of the whirl in the water is in the opposite direction, as

in Fig. 17. These rotations have been called clockwise whirls and anti-clockwise whirls, because the motion in Fig. 16 is in the same direction as the motion of the hands of a clock, and in Fig. 17 is in the opposite direction. These motions can easily be seen by sprinkling a bit of dust on the surface of the water.

If a smoking taper is held close over the opening in the water, near the center of the whirl, it can be seen that air is being drawn

FIG. 17



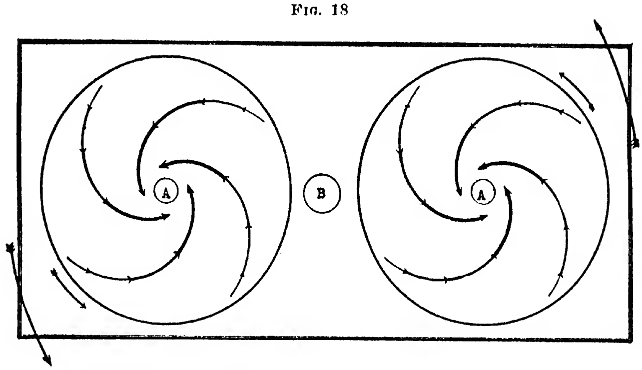
down from above into the central opening. If we now place the bowls on a board away from the center *B*, as in Fig. 18, and give the board a motion of rotation around *B*, then when the water is allowed to flow out of the bowls at *A* and *A'*, whirls will be generated having the same direction of rotation as that of the board.

The air moving toward central areas on the rotating earth acts in the same way as water moving toward a central area in a rotating bowl. Furthermore, it has been shown that when the weight, density, viscosity, etc., of different fluids are considered,

these atmospheric whirls obey the same laws of motion as other fluids and gases and the speed and direction of the motions can be accurately calculated when the different factors are known. The deflecting effect of the earth's rotation is small near the equator but increases with increasing latitude and approach toward the axis of rotation at the poles.

It matters not whether the air flows toward a central area where the air is cold or toward a central area where the air is warm, a whirling motion is generated in either case. In Fig. 18 the point B may be taken as the pole of the earth and the points A and A' points toward which masses of air are moving. In each

Fig. 18

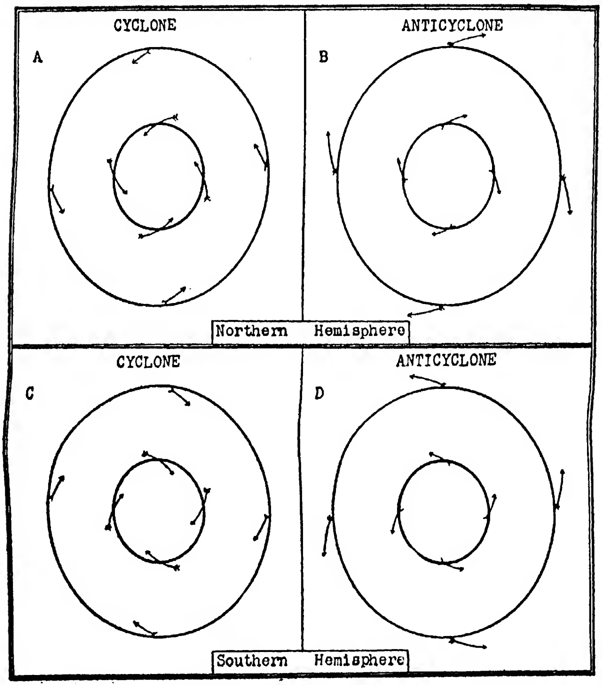


case whirls would be generated such as indicated in the diagram, provided the direction of rotation around B was as indicated by the arrows at the edge of the diagram. If the rotation is in the opposite direction, as it would be if one were looking down on the south pole of the earth, the rotation of the atmospheric whirls would be in the opposite direction. In the atmosphere two classes of whirls have been distinguished, in one of which the surface air flows inward and ascends, while in the other it flows outward from a central area and descends. The first is called a cyclone and the second an anticyclone. In Fig. 19, A represents a cyclonic circulation in the northern hemisphere and B an anticyclonic, while C represents a cyclonic circulation in the southern hemisphere and D an anticyclonic.

The air flowing in toward the warm waters of the north Atlantic in winter takes on a cyclonic circulation with the center somewhat to the south of Iceland (see Fig. 15). The cold air flowing out from the United States in winter shows an anticyclonic circulation

around a center in the region of Utah or southern California, while there is a tendency to a cyclonic circulation around the Great Lakes (see Fig. 7). These circulations are evidently due to temperature. Cold air is denser and heavier per unit mass than warmer air and under the influence of gravity presses in toward regions of warmer air which is lighter, and tends to lift it.

FIG. 10



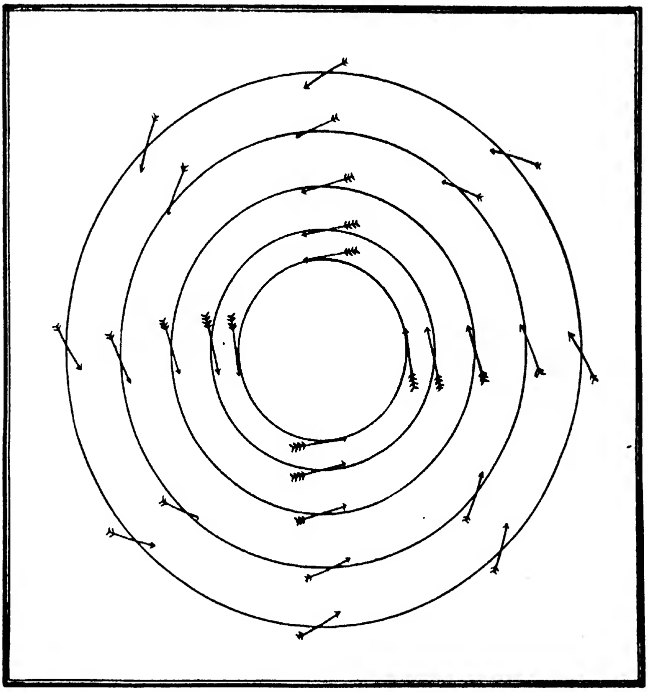
Surface Circulation of the Air in Cyclones and Anticyclones

Thus is set up a circulation with ascending currents such as is seen in the north Atlantic and the Great Lakes in winter while anticyclonic circulations are developed over the continents. In cold winters the surfaces of the Great Lakes freeze over and then they act like land areas.

In moving cyclonic systems in temperate regions the temperature up to a height of about 30,000 feet is lower in cyclones than in anticyclones, so that able investigators, like Hann, have been

led to believe that the cyclone is not the result of local differences of temperature, but rather the result of dynamic forces derived from the differences of temperatures between equator and pole. These cyclonic and anticyclonic whirls will be discussed more fully in a subsequent chapter. The most typical example of an

Fig. 20

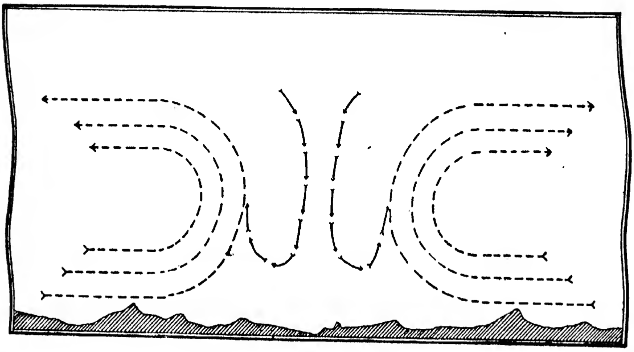


Surface Circulation in Well-Developed Cyclone

atmospheric whirl with inflowing surface air is furnished by a tropical cyclone. In these cyclones, the circulation of the air in the northern hemisphere is something like that shown in Fig. 20. At the outer circumference, the motions of the winds are relatively light, but steadily increase in velocity as they approach the center; also their inward component of motion becomes less and less with approach to the center until finally the air moves around the center in almost a perfect circle. These motions are

exactly what ought to result from a body having weight and inertia moving inward toward a central area. In violent cyclones there is a central area with a clear sky and warm dry air, even at night, proving, as will be shown later, that this air has descended from above. Observations at the earth's surface show that the lower air is moving inward toward the center, while the *observed motion of clouds show that it is moving out above, so that a section through the center would show vertical motions like those outlined in Fig. 21. The downward motion in the central region is as much a part of the cyclonic circulation as any* other, but is frequently overlooked. It does not always reach the

FIG. 21



Vertical Circulation in Well-Developed Cyclone

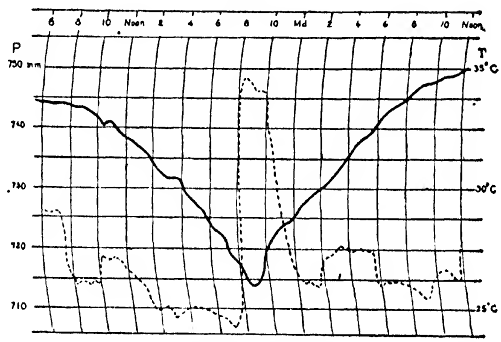
ground but, in any whirling mass, there is developed a centrifugal trend which becomes so great near the center that matter must be drawn from above to supply the place of that carried away from the center by centrifugal force. Humphreys has suggested that the presence of water particles in the cyclonic whirl increases the centrifugal action. By a series of interesting experiments, Sandström[11] showed that the same downward tendency of the upper layers is visible in whirls formed in water. If along a line running from the circumference to the center of the cyclone the pressure of the air columns is measured at selected points, it will be found that it decreases steadily. Such measurements are made by a barometer which may be considered as a balance, in one arm of which is the air column and in the other a column of

[11] Sandstróm, J. W.—*Monthly Weather Review*, p. 523, Washington, Sept. 1914.

mercury. The weight of the air is determined by the length of the mercury column necessary to balance the air column.

Fig. 22 shows a plot of the pressure along a line passing through the center of a tropical cyclone. It is derived from observations at Taito,[12] Formosa, September 16 and 17, 1912, when a tropical cyclone passed centrally over that point. This decreased pressure shows that there is the same tendency to a vacuum at the center as is shown by the absence of water in the center of a whirl in a basin, but no complete vacuum can occur on account of the downward flow of air from above.

FIG. 22



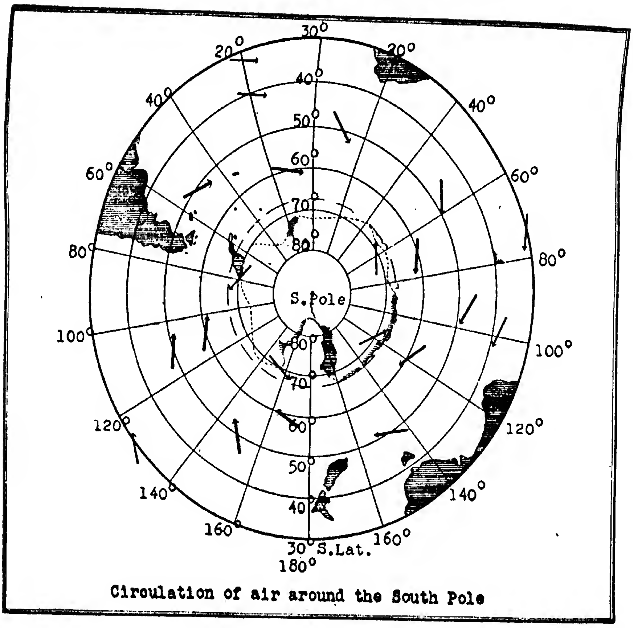
Barograph and Thermograph Curves in Tropical Cyclone at Taito, Sept., 1912—After Co-Ching-Chu

If the mean motion of the air be considered between 40° and the pole of the earth, there is found a cyclonic circulation around each of the poles. This circulation is most marked in the southern hemisphere, because the large expanse of water does not interfere with the free circulation of the air as do the land surfaces of the northern hemisphere. Fig. 23 shows a plot of this circulation from observations at the earth's surface. Fig. 24 shows a plot of the pressure across both of the earth's poles derived from the charts of Buchan[13] in the report of the Challenger Expedition. From these charts the mean pressure was determined for each ten degrees of latitude from 90° N. to 60° S., and these data were supplemented by those gathered by Moss-

[12] Co-Ching-Chu—*Monthly Weather Review,* p. 418, Washington, Sept. 1918.

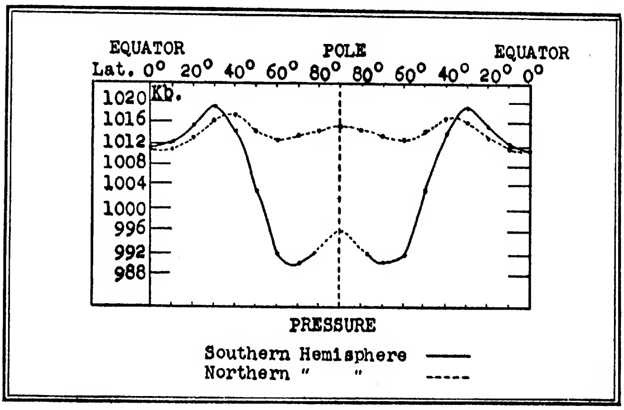
[13] Buchan, Alexander—*Report on the Scientific Results of the Voyage of H.M.S. Challenger,* Vol. 2, Part 5. London, 1889.

FIG. 23



Circulation of air around the South Pole

FIG. 24



Pressure for Each 10° of Latitude from Equator across Both Poles

man[14] from the observations of various polar expeditions. The mean results in millibars are as follows:

TABLE I

MEAN PRESSURE IN MILLIBARS

Latitude	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Mean Pressure, North..	1011	1011	1013	1016	1017	1014	1012	1013	1014	1015 mb
" " South..	1011	1012	1015	1018	1014	1003	992	990	991	--

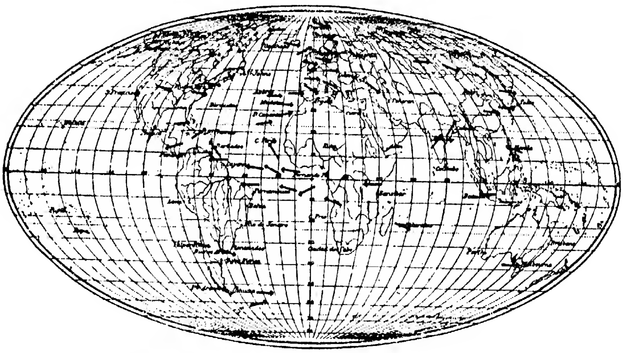
The mean pressure for 80° S. was determined from observations for four years at McMurdo Sound in mean latitude 78° S. These data were plotted by beginning with the pressure at the equator and plotting the mean values of the latitudes to 78° S., then extending the line across the pole from which there are insufficient observations to form a mean and resuming the plot at 78° latitude from whence the pressure was plotted back to the equator again. A similar plot was made across the northern hemisphere where the data are more complete, as shown by the lower curve in Fig. 24. In this way the deep barometric depression in the south polar regions and the lesser depression in the north are clearly brought out, and there is seen to be a distinct resemblance between the more or less permanent polar cyclones and the transient cyclones of the tropical belt, even to the extent of a vertical descent of air which is clearly indicated in the cyclone around each pole by the outward blowing winds near the central areas. The low pressure around the south pole has long been a puzzle to meteorologists. It seems clearly due to the rarefaction resulting from the centrifugal force developed in air circulating around a central point, as explained by Ferrel.[15] Just as water is more depressed in the center of a bowl revolving rapidly than in one revolving slowly, so the air is rarer, and therefore the barometer is lower near the pole of the southern hemisphere around which the air is circulating rapidly than it is near the pole of the northern hemisphere around which there is a feebler circulation. The air circulation is stronger around the south pole because in the southern hemisphere there are less land masses with their mountains and less convection currents to retard the rapid movements of the air caused by the great contrast of

[14] Mossman, R. C.—"The Meteorology of the Wedded Quadrant and Adjacent Areas." *Trans. R. S. E.*, Vol. 17, Part 1, 1909; "On a Sea-Saw of Barometric Pressure, Temperature, and Wind Velocity between Wedded Sea and Ross Seas," *Roy. Soc. of Edinburgh*, Edinburgh, 1915.

[15] Ferrel, W.—*A Popular Treatise on the Winds*, pp. 133–145, New York, 1889.

temperature between the equator and the cold Antarctic continent. In actual conditions there is a chain of smaller cyclones circling around the pole, but the mean result is the same as if there were one large cyclone. Observations of air movements at all heights are by no means complete, but the large collection of the movements of the clouds by Hildebrandsson supplement the vast collections of surface winds now available and which were so admirably set forth by Maury in his "Physical Geography of the Sea." The circulation of the higher clouds as given by Hilde-

Fig. 25



Air Movement in the Cirrus Level, 5 to 7 Miles

brandsson is shown in Fig. 25, supplemented by some additional data from other sources.

It is seen from this chart that within ten degrees of the equator the movement of the highest clouds and of pilot balloons at the height of 5 to 7 miles is chiefly from the east. At 10° to 20° N. the air comes from the southeast, as shown by the observations between Manila and the West Indies. At 20° to 30° N. the upper air movement is from southwest. Between 30° and 40°, it is almost directly from west; while between 40° and 60° N. it is from some point north of west. In the southern hemisphere there are found winds from northwest at Mauritius and from nearly west at Buenos Aires and Melbourne.

These clouds clearly indicate a motion outward from the equator to about 30° N., with a prevailing direction from southeast in the northern hemisphere. In the temperate and northern latitudes the motion is nearly from west to east, but with a

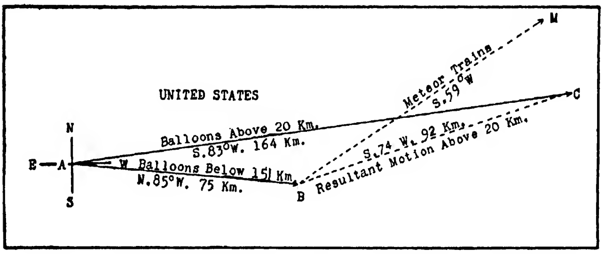
slight component of motion toward the equator so that from the Arctic Circle to the latitude of 40° there is a distinct tendency toward the equator. Observations at the South Orkneys (60° 45′ S., 44° 39′ W.) show also an inclination of the highest clouds toward the equator, thus indicating a similar drift in both the northern and southern hemispheres. The measured heights of these cirrus clouds show that they are lowest in the Arctic region and higher toward the tropics. This fact probably indicates an upward movement of the air stratum as the clouds progress toward the equator. The general features of the circulation between poles and equator are outlined in Figs. 29 and 30.

Observations of the surface air in the Arctic region indicate that there is a component of movement outward from the pole to latitude about 65° or 70°, but between latitudes 40° and 60° there is a distinct component of movement toward the pole, while from latitude 20° or 25° there is a wind with a component of movement toward the equator called the "trade wind."

The air movement sketched in at the highest level is as yet largely theoretical, although such evidence as I have been able to collect, indicates its existence. Sounding balloons have frequently been sent up to heights exceeding 12 miles (20 km.), and occasionally to heights exceeding 20 miles (32 km.). It is difficult to follow and observe the motions of balloons at these great heights, and very few have been observed; but it is possible to get an idea of the motion of the upper air by plotting the directions and distances to the points of landing, and comparing them with those of balloons reaching a lesser altitude. In the *Sounding Balloon Number* of the Mount Weather Observatory of the U. S. Weather Bureau Bulletin, Vol. 4, Part 4, pp. 184-185, a table is given of the direction and landing point of the sounding balloons sent up from Omaha, Huron and Indianapolis in the years 1909 to 1911. Sixteen of these exceeded 12.5 miles (20 km.) and their mean direction of travel was from S. 83° W., the distance traveled was 103 miles (165 km.). On the other hand, seventeen balloons which reached heights between 6¼ and 9 miles (10 and 15 km.) showed a mean drift from N. 85° W. to a distance of 47 miles (75 km.). These results are plotted in Fig. 26. If *AB* is the drift in the lower air, and *AC* is the drift of the whole air up to a mean height of about 15 miles, then there must be in the upper air a component of motion from the south whose velocity and direction can be approximated by the resultant line *BC*. This line indicates a mean direction of the upper currents from S. 74° W. and a velocity as great as that of the lower currents.

The sounding balloons sent up from the Observatoire Royal de Belgique,[16] 1910 to 1914, were treated in the same way. Seventeen balloon ascents were found whose maximum heights were between 12.5 and 20 miles (20 and 32 km.). The mean direction of travel of these was from N. 48° W., and the distance traveled 25 miles (40 km.); while the mean direction of twenty-one balloons whose record did not exceed 12.5 miles (20 km.) was from N. 38° W. and distance traveled 22 miles (36 km.). These results are shown plotted in Fig. 27 and the resultant BC indicates a weak current from S. 75° W. between 12.5 miles and 20 miles (20 and 32 km.) above the earth's surface. However, owing to the small number of balloon ascents and the uncertainty of maxi-

FIG. 26



Movements of the Atmosphere in the Central and Eastern United States

mum heights of several of the balloons whose records did not extend beyond 12.5 miles (20 km.), this resultant direction can be accepted only provisionally. It is certain that most of the drift of the balloons is in the stratum below 12.5 miles (20 km.) and there are relatively weak currents for some distance above that level.

The only evidence of atmospheric drift at very great heights is the drifting of meteor trails. Professor C. C. Trowbridge gives in the *Monthly Weather Review* of the U. S. Weather Bureau for September, 1907, a list of the directions of travel of more than sixty cases where the direction of drift of meteor trails was observed at heights of 40 to 70 miles above the earth's surface.

In regard to these he says:

"The drifting motion of meteor trains, so often observed, is unquestionably due alone to atmospheric currents. The observa-

[16] Observatoire Royal de Belgique—*Annuaire Meteorologique*, 1910, 1911, 1912, 1914.

tions of these train movements is the only means by which data concerning the motions of the extreme upper regions of the earth's atmosphere can be obtained. In a recent paper over sixty train drifts have been collected, tabulated and discussed, and several facts concerning the atmosphere brought to light. Many of these trains were above the 50 miles altitude and recorded by the most accurate meteor observers, Denning, Herschell, Backhouse, Booth, Newton, Barnard, Twining, etc. A statistical study of trains has shown that many, at least of those seen at night, are self-luminous. The remarkably persistent light of the meteor train is in all probability a gas phosphorescence, since in many respects it is similar to the gaseous afterglow which is found in a vacuum tube by electrical discharges."

For the reason that the light of the meteor train may be electrical, it appears doubtful to Cave that they show atmospheric drift. But the very irregularity of their movements seems to be evidence of atmospheric motion, and until other methods of exploring these great heights are found the meteor train furnishes the only evidence we have of air drift at these great heights.

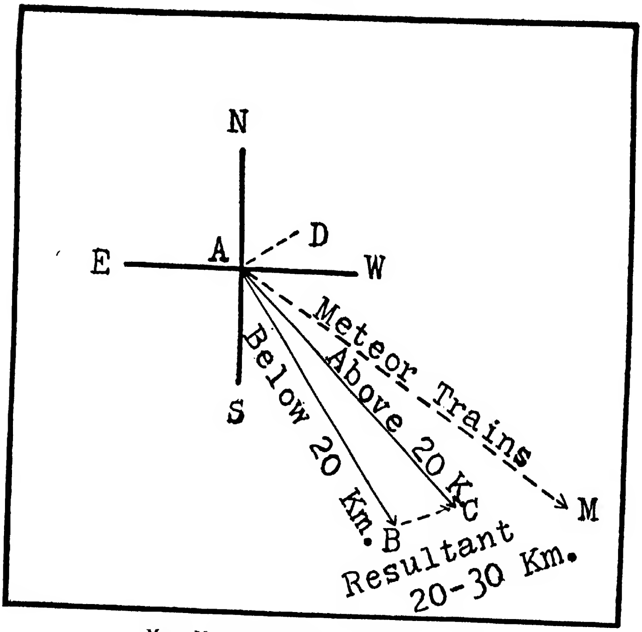
A plot of the thirty-five meteor trains observed over the United States shows a mean drift from S. 59° W. As there were few velocities recorded, each direction was given the weight of one. This mean drift is shown by the broken line *AM* in Fig. 26. In this plot, *AB* shows the mean drift of the air below 9 miles (15 km.), *AD* the resultant drift between 6 and 19 miles (10 and 30 km.), and *AM* the mean direction of drift of the meteor trains, but not their velocity. The evidence in these cases shows that, over the United States, the component of atmospheric drift from the south increases with increasing height. In the case of Great Britain, the mean of twenty-two meteor trains is from N. 59° W. In this region it appears that although there is an increase in the west to east component, there is still found a component from the north, even at great heights; but if the mean of all the observed trails in the northern hemisphere is determined, the balance shows a strong west to east current with a slight component toward the north (see Fig. 27). Hence, the evidence of a component of drift from the south at great heights is not conclusive, but the bulk of the evidence favors it.

In the southern hemisphere, the only observations at a great height are those made with pilot balloons under the supervision of Dr. W. Van Bemmelen [17] in Batavia, six degrees south of

[17] Van Bemmelen, W.—"Die Wind-Verhältnisse in den oberen Luftschichten nach Ballonvisierungen in Batavia," 1911.

the equator. These show that the monsoon winds extend to a height of about 4 miles (6.25 km.). From 4 to 7 miles (6.25 to 10.5 km.) the mean wind direction is from east; while from 8 to 11 miles (12 to 17 km.) the mean wind is from a point north of east. Hence, at the greatest heights reached there is a component of motion from the equator toward the south pole.

FIG. 27



Mean Movement of Air in Western Europe

Over Lake Victoria Nyanza,[18] directly under the equator, evidences were found of a westerly wind at a great height, indicating a backward moving current in that region like that in the equatorial waters in some parts of the Pacific.

There are also general reasons why a current directed from equator to pole exists at great heights:

1. The sounding balloons, both in the United States and

[18] Berson, Arthur—"Bericht über die Aerologische Expedition des Königlichen Aeronautischen Observatoriums nach Ostafrika im Jahr 1908."

Europe, show that the mean drift of the atmosphere up to 10 miles is from some point north of west, and, hence, has a component of motion from pole to equator. Hildebrandsson's[19] collection of cloud observations shows that this condition prevails throughout the temperate zone (40° to 60° N.) up to the level of the highest clouds. But it is evident that, if the mass of the air as a whole below 10 miles is moving from the pole, there must be a higher stratum where an equal mass of air is moving toward the pole or else a vacuum would be left at the pole.

2. The temperature distribution shown by sounding balloons finds a reasonable explanation if there exists a high, slowly descending current directed from equator to pole, such as is indicated by the temperature distribution in Fig. 10.

Following the reasoning of W. H. Dines in the *Monthly Weather Review* of November, 1915:

"Before observations were set on foot no one would have expected that the lowest natural temperature that mankind has measured would be found at some 10 miles height over the equator, yet so it is. The actual mean value 193° A. (— 80° C. or — 112° F.) may be doubtful, but the value is certainly far below that found at the same height in temperate latitudes. The highest mean (upper air) temperature is given by Petrograd (Pavlovsk), the station of highest latitude from which regular observations are obtainable. It seems to me that there is one and only one feasible explanation. The low temperature must be due to the general ascent of the air, and it must occur in spite of, and not in obedience to, the radiative conditions. Radiant energy is most intense at the equator, both direct and indirect. The earth and lower layers of air are warmer and the radiation they send upward is more intense. It is utterly impossible that this can be checked by a veil of cirrus or other cloud, for if checked it can only be by being absorbed or reflected; if reflected, it must raise the lower temperature still more; if absorbed, it must raise the temperature of the absorbing body until the latter gets so hot that it radiates outward as much heat as it is receiving from below. Thus inevitably air at 16 kilometers (10 mi.) over the equator, so far as radiation is concerned, with intense radiation coming from above and hot damp radiating layers below, must be warmer than air at the same level over the plains of northern Russia, with no appreciable solar radiation from above and a surface of snow below having a

[19] Hildebrandsson, H. H.—"Rapport sur les Observations International des Nuages, Upsala, 1905"; also "Resultats des Recherches Empiriques sur les Mouvements Généraux de l'Atmosphere."

temperature not much above the freezing point of mercury. Yet the air high up over the snow-covered plain is about 54° F. warmer than that over the rank, steaming jungle of the tropics.

"The fact can be explained if we suppose a steady though slow rise of air in the tropics and a corresponding fall in regions nearer the poles."

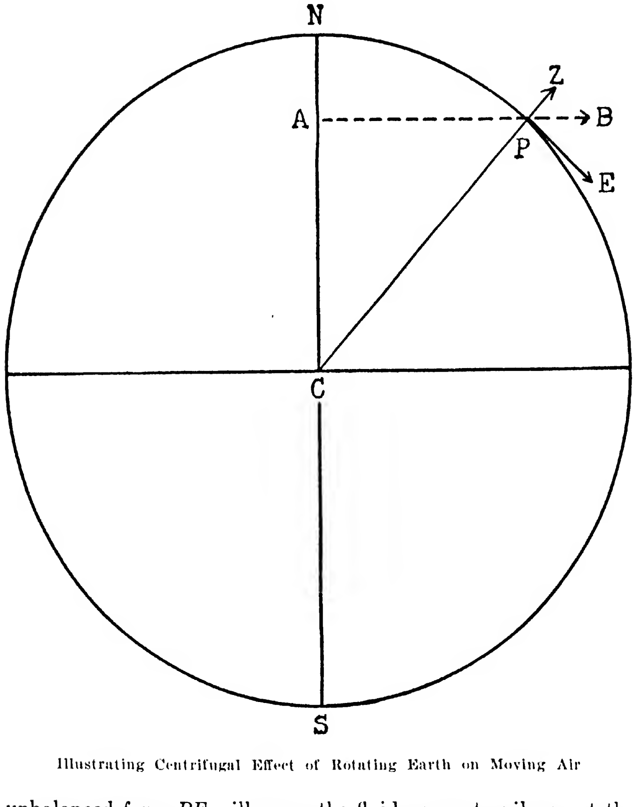
Also, it may be added, a strong current of air with a component of motion toward the equator, slowly rising as it advances, explains the sudden inversion of temperature at its upper limit (6 to 9 mi.), for here we have a cold current moving beneath a warmer current. It also explains the rapid decrease of temperature with increasing height in the lower current and the consequent instability and convectional overturning in that part of the atmosphere called the *troposphere* for the current at 5 to 9 miles is overrunning a warmer surface current. Observations in all parts of the temperate zone indicate that the air immediately beneath the *stratosphere* (see Fig. 10) has a component of motion toward the equator, while the air near the earth's surface in those latitudes has a component of motion toward the pole. Hence, the first is coming from a cold region of the earth and is overflowing the surface air coming from a warmer region. It is a logical consequence that there is a rapid vertical decrease of temperature and instability. It is also a logical consequence that air at 6 to 9 miles in latitudes north of 20° is colder than the air immediately above it, which either has very little motion or else is moving from equator to pole.

It seems contradictory to experience and to the facts previously stated that cold air should move with a slant upward and be replaced, in part at least, by warmer air coming in beneath from an opposite direction. The explanation of this lies in the centrifugal force generated by the air's motion. Under the influence of rapid rotation, heavy and light fluids and gases behave in a different way from their action under usual conditions. If a mixture of milk and cream is poured into a rapidly rotating receptacle with a hollow, perforated axis lying in a horizontal direction, the cream will pass to the center and flow out at the end of the hollow axis; but, if the rotation of the vessel is stopped, and the mixed milk and cream again poured in, the cream will rise to the top of the vessel and the milk flow out at the axis.

In Fig. 28 let *NS* represent the axis of rotation of the earth, then a particle at *P*, revolving around the axis *NS*, would tend to

move outward in the direction *PB* under the influence of centrifugal force. The force *PB* may be resolved into two components, one *PZ*, directed away from the center of the earth which is counteracted by the pull of gravity, and the other *PE*, directed toward the equator. If the matter acted on is a fluid or gas, this

Fig. 28



Illustrating Centrifugal Effect of Rotating Earth on Moving Air

unbalanced force *PE* will cause the fluid or gas to pile up at the equator until the increased mass under the influence of gravity has a backward pressure equal to the force *PE*. In this final condition of equilibrium the air mass, supposing that we are dealing with the atmosphere, bulges out at the equator and is flattened at the poles. Having reached this condition of equilibrium,

suppose that the air at any part of the earth's surface begins to move from west to east, that is in the direction of the earth's rotation, the result is equivalent to an increased rotation of the air and, consequently, to an increase of the forces PE and PZ. In other words, in the case of air moving from the west, a force is developed which drives it toward the equator and also makes it lighter than air under normal conditions. The opposite is true of air moving from the east. Ekholm [20] has shown mathematically that, given the observed high velocities from the west in the stratum of air at 5 to 8 miles, these forces are sufficient to modify the movements of air arising from differences in temperature. Expressed in another way, air moving from the west with sufficient velocity becomes lighter than warmer air moving from the east or south, so that, while its velocity is maintained, the cold air may be lifted up and overflow the warmer air coming from equatorial regions. Calculation indicates that the centrifugal force generated by winds moving from the west at observed velocities is not sufficient of itself to overcome any considerable difference of pressure on a level surface due to observed differences of temperature; but, where the pressure gradient due to the combined effect of temperature and the horizontal movement of the wind is in balance, the centrifugal force of the wind becomes important. If under the influence of westerly drift, the air moves upward, there will be a tendency for the air to move inward along the gradient toward the diminished pressure as long as the barometric gradient increases with increasing height; but as soon as the pressure gradient decreases with elevation, the horizontal velocities acquired at a lower level will be greater than those necessary to balance the gradient, and the air will move outward against the gradient with diminishing velocity. This appears to be what happens in the atmosphere at heights of 5 to 7 miles (8 to 11 km.). See dotted arrows in Fig. 29.

All the work needed to maintain this interchange of air between equator and pole is to overcome air friction, and, since this is not large, the required force should not be large.

The balanced pressure gradient in the lower air is the result of the temperature and wind movements of the whole atmosphere, including the part above 8 miles which must be considered, as well as that below. Owing to lack of observations, the theory cannot yet be submitted to rigid calculation.

[20] Ekholm, Nils—"On the Influence of the Deviating Force of the Earth's Rotation on the Movements of the Air," *Monthly Weather Review*, Vol. 42, No. 6, p. 330, Washington, June 1914.

Figs. 29 and 30 show the general circulation of the atmosphere as nearly as can be determined from observations up to the present time.

Fig. 31 shows the mean distribution of atmospheric pressure at sea level for the year over the surface of the world. It is seen that there is a belt of low pressure around the globe in the equatorial regions, belts of high pressure on each side about the 30th parallels north and south and belts of low pressure about

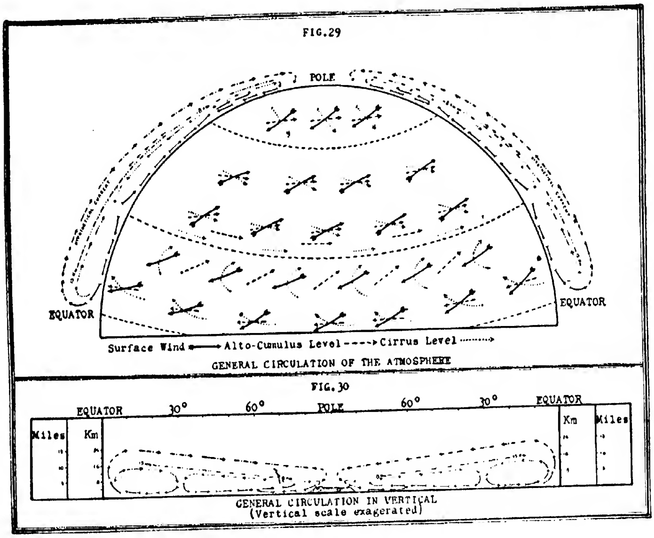


FIG. 29

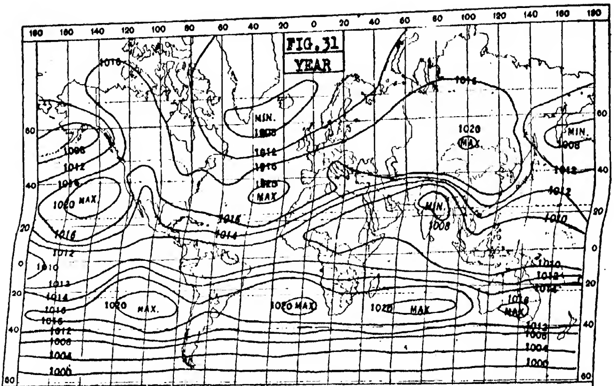
GENERAL CIRCULATION OF THE ATMOSPHERE

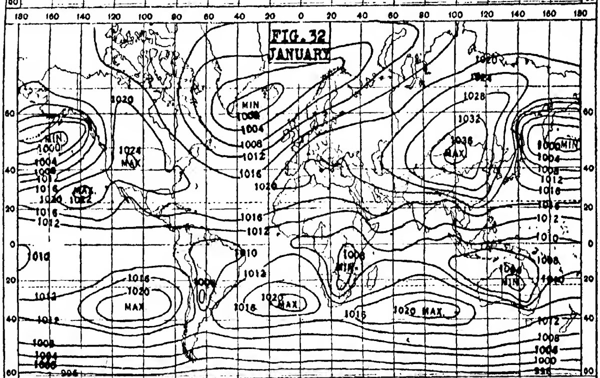
FIG. 30

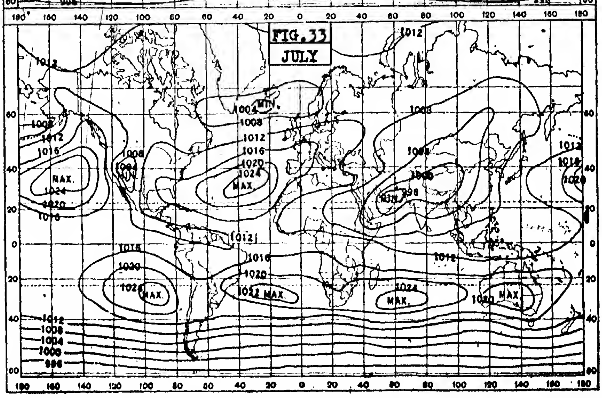
GENERAL CIRCULATION IN VERTICAL
(Vertical scale exagerated)

the 60th latitude. Within each of these belts, however, are centers of higher or lower pressure. In the equatorial belt of low pressure the lowest pressure is found in the region between India and New Zealand over the warmest waters of the world. Near the 30th parallel of latitude the highest pressures are found over the coldest waters of that latitude, and near the 60th the lowest pressures are found somewhat to the west of the regions of warmest water for the same latitude.

Fig. 32 shows the distribution of pressure for January, and Fig. 33 for July. These figures bring out the effects of solar radiation on the continents and oceans when the sun is at its farthest point south or farthest point north of its mean position.



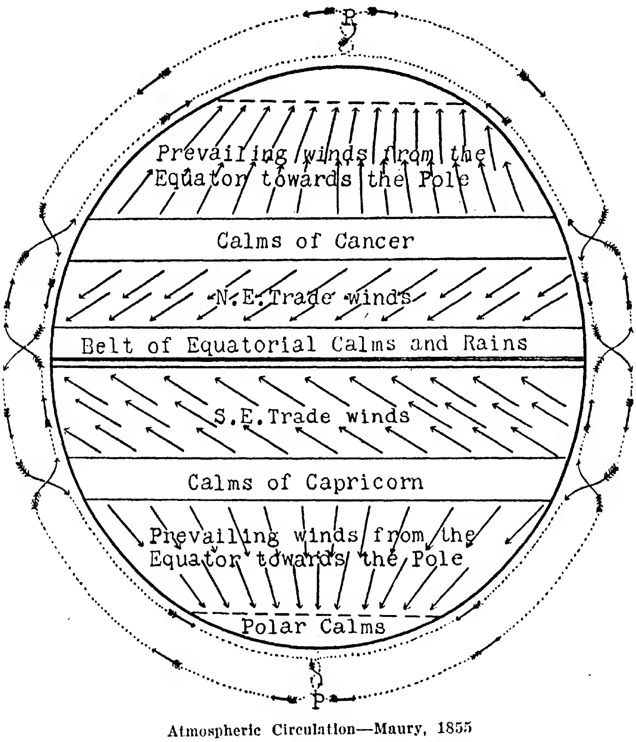




Normal Distribution of Atmospheric Pressure in Millibars

The theory of the general atmospheric circulation outlined above conforms closely to what is known as the Ferrel theory. Admiral Maury,[21] James Thompson [22] and William Ferrel [23] all

FIG. 34



Atmospheric Circulation—Maury, 1855

contributed toward the development of this theory. Figs. 34 to 37 illustrate the development of the theory between 1855 and 1860.

Ferrel brought to the study of the atmosphere a profound knowledge of mechanics and mathematics and submitted the theory to the test of calculation with all the material available

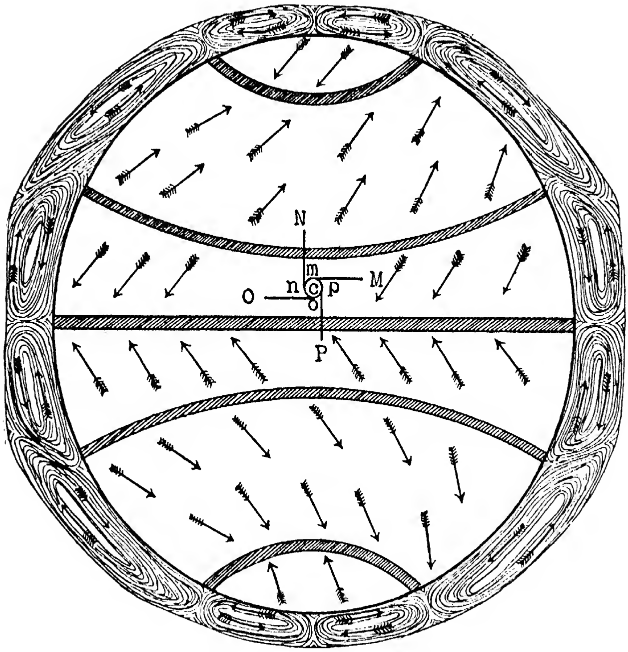
[21] Maury, M. F.—*Physical Geography of the Sea and Its Meteorology,* London, 1855.

[22] Thompson, James—"The Grand Currents of Atmospheric Circulation." *British Association for the Advancement of Science,* 1857.

[23] Ferrel, William—"The Winds and Currents of the Ocean," *Nashville Journal of Medicine and Surgery,* 1856; "The Motions of Fluids and Solids on the Earth's Surface," *Runkle's Mathematical Monthly,* 1858–1860.

thirty years ago. His work has given the great weight the theory has held up to the present time, although it is still a matter of controversy. Since Ferrel's time there has been a great accumulation of new material; the *stratosphere* has been discovered by Teisserenc de Bort and the drift of the air in the cirrus level has

FIG. 35



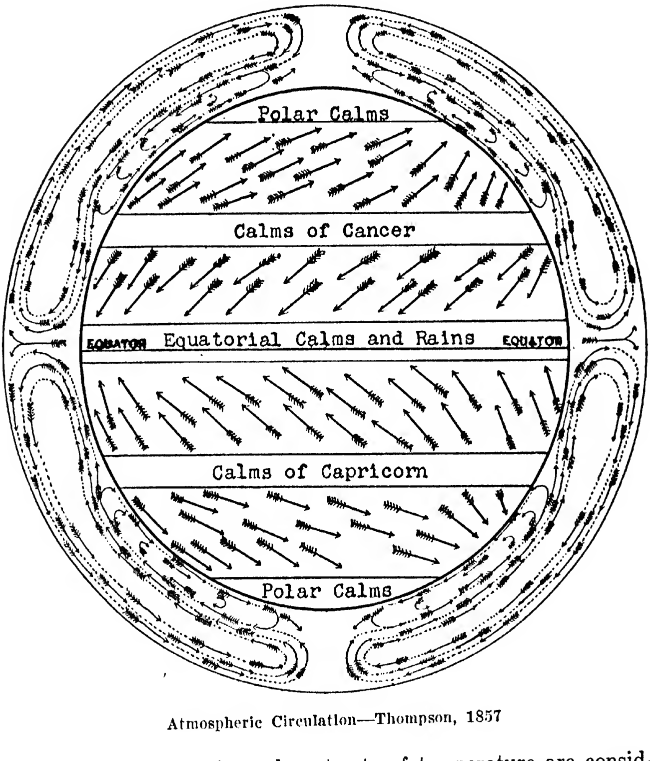
Atmospheric Circulation—Ferrel, 1856

been developed by Hildebrandsson; but there is a lack of sufficient observations in the highest stratum of the atmosphere and material is still needed for a rigid verification of the theory. However, his theory furnishes the simplest and most plausible explanation yet obtained of the general circulation and of the motions of the atmosphere under the influence of heat and gravity on a rotating body like the earth. The theory will undoubtedly need to be modified when the facts are fully known, and it may be

possible to explain the circulation without considering the currents in the upper atmosphere.

Bjerknes [24] has recently offered a new mathematical treatment of the problem. His scheme of the general atmosphere circulation is illustrated in diagrams *A* and *B* in Fig. 38.

FIG. 36



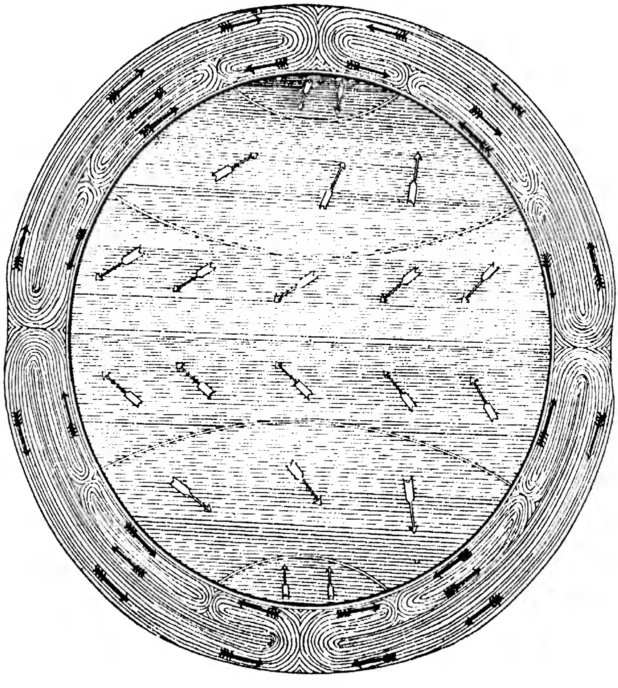
Atmospheric Circulation—Thompson, 1857

The effects of horizontal contrasts of temperature are considered in Chapter VIII and the laws there considered appear to be sufficient to explain the permanent cyclones and anticyclones of temperate regions and may perhaps be developed to include the circulation around the poles.

[24] Bjerknes, V.—*On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmospheric Vortex and Wave Motions*, Christiana, 1921.

If the current of the *stratosphere* form a part of the general circulation, as suggested in Fig. 29, there must be a mingling of the currents at the plane of meeting caused by wave motion and eddying so that the lower part of the stratosphere is cooled some-

FIG. 37



Atmospheric Circulation—Ferrel, 1860

what by mixture with the troposphere and carried with it toward the equator.

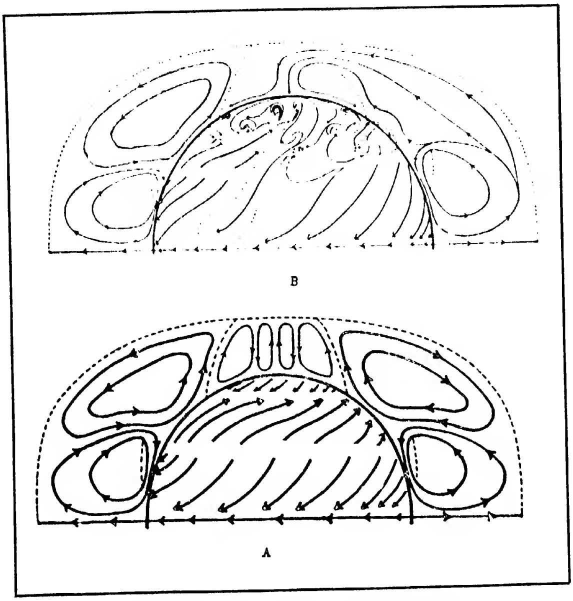
Ferrel[25] points out that the total movement from the east must balance the total movement from the west or else the earth's rotation would be accelerated or retarded. Observations of sounding balloons, clouds and kites show that there exists a predominance of air movement from the east within the tropics and a

[25] Ferrel, William—*A Popular Treatise on the Winds,* pp. 101–121, New York, 1889.

predominance of air movement from the west north of latitude 30°.

When the atmosphere is once in motion in the manner described, the results of its motion may be considered as a problem in mechanics. In such a circulation around a central area the heavier air tends to move to the outer part of the circulation and

Fig. 38



Atmospheric Circulation—Bjerknes, 1921
A. Mean Condition. B. Condition at Some Given Moment

the lighter air to move toward the center, just as in a centrifugal separator the cream goes to the center and the heavier milk to the outside of the rotating cylinder. Hence, as the cold polar air is heavier, it would tend to move toward the equator and be replaced by the movement of the warmer lighter air moving from equator to pole.

Because friction is greatest near the earth's surface the velocity of the circulation is diminished in the lower air and is greatest above. For this reason the air is carried outward by the greater centrifugal force above and drawn in below except very near the

pole, where the great surface cooling increases the density so much as to overcome the lifting effect.

Thus by the mechanical process of rotation the pressure would be lowered at the poles and increased at the equator; but, as the process of heating is continuous at the equator, the dense air does not reach the equator but forms a ring of high pressure at some intermediate latitude such as is observed on the earth, and this ring develops a secondary circulation which modifies to some extent the primary circulation described.

The polar whirl is what Ferrel terms a cold air cyclone, and in such a circulation there must be a descent of air near the center to supply the energy for the whirl, so that there remains a small surface anticyclone in the polar region as an essential part of the atmospheric circulation. To maintain a whirl against the loss of motion resulting from friction, an outflow of surface air near the center is just as necessary as the outflow of water in the center of a bowl is necessary for maintaining the whirl in a basin of water. In the case of the polar anticyclone, the cause of the high pressure is the cold air, and the outflowing air below is due to its greater density as the result of surface cold. On the other hand, the high pressure belt near the tropics results from the centrifugal force derived from the circulation around the pole. The air descends and is warmed by compression so that up to a height of about 5 miles above the earth, the air at 20° latitude is warmer than the air at the same level in other regions, as will be seen by reference to Fig. 10.

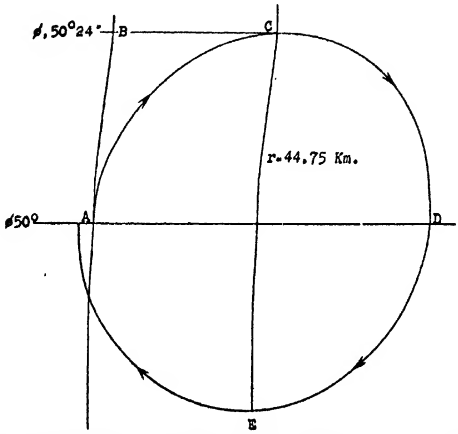
Before leaving the complex subject of the influence of the earth's rotation on the winds, it is well to call attention to another result on winds moving from north or south.

Looking at a diagram of the polar regions, like Fig. 23, it is evident that winds moving from the equator to the pole are moving toward smaller areas and hence, in order to preserve a steady flow, the wind must continuously increase in velocity, while in the opposite case of a steady wind moving from the pole, it must decrease in velocity with the diverging lines of longitude. Streams of air maintained by gradients causing them to move directly north or south are not stable and soon disappear. In general, wind velocities increase from the tropics to the Arctic Circle, and with increased wind velocities go increased pressure and temperature changes.

However, a particle of air directed poleward does not move in a curved path with steadily increasing velocity, for from moment to moment, as the air particle changes its path, the

deflective force of the earth changes and as the deflective force is at right angles to the motion of the air particle it tends to move in a circle unless restrained by a persistent pressure gradient, as recently explained by H. W. Clough,[26] amplifying earlier views of W. M. Davis. If a body were projected northward from a point in the northern hemisphere, as, for example, from a point *A* in Fig. 39, and moved without friction on a level surface, it would be steadily deflected to its right by the earth's rotation and would follow a circular course, returning to a point slightly west of its

Fig. 39



Illustrating effect of Earth's Rotation on Free Moving Particle of Air. After H. W. Clough

starting point. If started from 50° N. with a velocity of 5 meters per second (11 mi. per hr.) it would recurve at 50° 24′ N. and recross its path again at *D*. The time required for a complete revolution would be 15.7 hours. Hence, it is evident that air can continue moving in steady streams only when there are developed extensive pressure gradients.

Shaw [27] and Lempfert also in the case of the moving cyclones of temperate regions have followed the same air mass along the earth's surface as nearly as possible by a series of bi-hourly

[26] Clough, H. W.—"The Principle of Angular Momentum as Applied to Atmospheric Motion," *Monthly Weather Review,* Vol. 45, No. 8, p. 463, Washington, August 1920.

[27] Shaw, W. N., and Lempfert, R. G. K.—"The Life History of Surface Air Currents," *Meteorological Office Publication No. 174,* London, 1906.

observations and find that the same air mass does not move steadily in toward the center of cyclones and outward from anticyclones but rather in curved tracks looping backward on themselves or else rising upward over the air masses in front or descending to the earth in the rear, so that no part of the whirl can be considered to have a continuity of motion like water in a basin.

Anyone who has had occasion to make a prolonged balloon voyage at nearly a constant height has experienced this same tendency of moving air to turn in curved paths.

Hence, in dealing with air movements they must be considered from moment to moment as causing or being caused by pressure gradients which are the result of temperature differences and of motions taking place simultaneously at all levels in the atmosphere. Air does not act like a solid mass, but each particle must be considered as moving under the influence of forces acting on the point where it is located, but each particle is subjected to gravitational and centrifugal forces which bring about the observed conditions, previously explained. Up to the present, no adequate theory has been developed by means of which a meteorologist may start from temperature contrasts and compute pressure gradients arising from these contrasts and finally compute the adjusted pressure gradients resulting from the temperature contrast and from the air motion, for the observed pressure is due to both causes.

Owing to this difficulty Shaw [28] and Marvin [29] prefer to start from observed gradients and from these derive mathematically the necessary air movements for maintaining equilibrium. This process has led to a very satisfactory agreement between pressure gradients and air movements except near the earth's surface, where friction is still an unknown quantity.

In the chapter on cyclones and anticyclones (Chapter VIII) there is developed a theory which shows that contrasts of temperature in adjacent regions is sufficient to explain the source of energy and the air movements in cyclones and anticyclones, so that, on having the necessary data, one might start from temperature gradients and compute the resulting cyclonic and anticyclonic phenomena. In that chapter the general atmospheric circulation is again reviewed briefly in the light of the principles developed in the study of cyclones and anticyclones.

[28] Shaw, Sir Napier—"The Relation of the Winds to the Distribution of Barometric Pressure, *Manual of Meteorology, Part 4;* London, 1919.

[29] Marvin, C. F.—"The Law of the Geoidal Slope, etc.," *Monthly Weather Review,* Vol. 48, No. 10, p. 569. Washington, October, 1920.

CHAPTER II

THE DAILY PERIOD IN THE WEATHER

SUMMARY

Owing to the rotation of the earth on its axis, daily changes in the amount and intensity of solar radiation received at any place occur which cause daily periods in the weather. The daily periods are shown to depend greatly on the quality and the form of the earth's surface in any region. The ranges are different over land and water, over sandy plains and grassy slopes, over valleys and mountains, different on clear days and cloudy days and different at the earth's surface and in the free air. They are also dependent on the latitude, the daily ranges being large near the equator and very small near the poles.

There is found, moreover, a half-daily period in the pressure which decreases in range from the equator to the poles, but is remarkably independent of the form or condition of the earth's surface over which it passes.

Charts are given showing the progress of the daily and half-daily changes of pressure around the world. The twenty-four hourly changes jump from continent to continent, while the twelve-hour changes move around the world with perfect regularity and with the precision of clockwork. The winds are found to show complex daily changes in direction and velocity, partly resulting from the daily changes in pressure and partly dependent on the vertical interchange between the surface air and the air above it. Daily changes varying with the environment are also traced in cloudiness and rainfall.

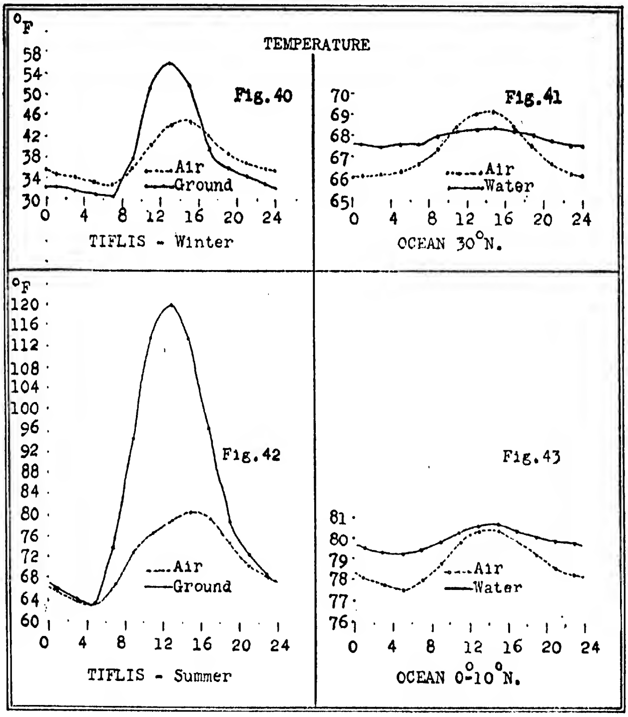
INTRODUCTION

The rhythmic rotation of the earth on its axis and its annual revolution around the sun bring the sun back to the same position with such regularity that the daily and annual changes in the state of the atmosphere are frequently regarded as features of climate, as in one sense they are. But although these changes occur with perfect regularity in time, they vary greatly in intensity and this variation makes them a part of the weather. Additional variations in the intensity of the daily and annual period are brought about by variations in the intensity of solar radiation, so that a study of these daily and annual changes is an essential part in understanding the basis of weather changes in general.

THE DAILY PERIOD IN TEMPERATURE

The first of the daily periods to be considered is that of temperature. It is a matter of common observation that the air

grows warmer during the day and colder at night. The part of the earth illuminated by the sun is gaining heat, while the part in shadow is losing it. The highest temperature of the day, however, is not at noon, when the sun is highest above the horizon, but occurs two to three hours after noon, while the minimum



The Daily Period in the Temperature of the Air over Land and Ocean

temperature of the day occurs normally a short time before sunrise. Daily curves of temperature plotted from observations at intervals of two hours are shown in Figs. 40 and 42 for Tiflis, a midcontinental station, 41° 43′ N., 44° 48′ E.

The continuous curve in Fig. 40 shows the mean change in temperature of the ground for the winter half year from hour to hour, and the dotted curve shows the simultaneous changes in the temperature of the air. In Fig. 42, the continuous curve

shows the mean changes in the temperature of the ground for the summer half year, and the dotted curve that of the air. The day parts of the curve between sunrise and sunset (about 6h. and 18h.) are symmetrical curves, but the night portions approach more nearly to a straight line sloping downward from sunset to sunrise. This difference arises from the different ways in which the ground and the air are affected by the incoming solar energy by day and the continuous outward radiation of energy into space which modifies somewhat the effect of the solar radiation by day but acts alone by night, so that, according to Perntner,[1] the two parts need entirely different mathematical expressions.

The curves show that the ground becomes much warmer than the air in the daylight but is as cold as, or colder than, the air at night. It is evident that the air gets its heat by day chiefly by contact with the soil which is a powerful absorber of solar heat. By the absorption of radiant energy coming from the sun, the temperature of the soil rises just as does that of a piece of rough metal held before the open door of a furnace; and the air over the soil is heated, just as the air is heated over a hot stove by contact with the metal top. The air begins to ascend at the places of greatest heat and colder air descends to replace it. Thus, there is produced an active vertical circulation of the air during the hottest part of the day. But the ascending air cools by expansion as it rises, and, at no great height, becomes as cool as the air surrounding it. The curves also show that the maximum temperature of the ground lags behind the maximum intensity of solar radiation less than does the temperature of the air.

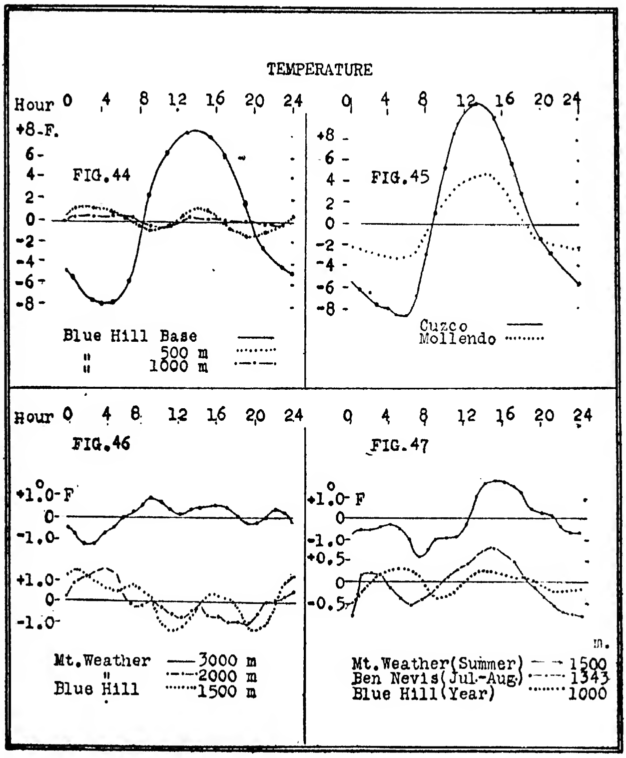
The daily variations in the temperature of the water and air in mid-Atlantic[2] at 30° N. and at 0° to 10° N. are shown in Figs. 41 and 43. The variation of temperature in and over the ocean surface is so small, as compared to that of the land, that the plots in Figs. 41 and 43 are made on twice the vertical scale of those of Figs. 40 and 42. It is seen from these plots that the variation in the temperature of the air over the ocean is greater than that of the surface water. In equatorial regions, the temperature of the air is lower than that of the water throughout the day. This fact and also the great daily range prove that the daily change in the temperature of the air is not derived from the daily change in the temperature of the water, but represents a direct absorp-

[1] Perntner, J. M.—*Monthly Weather Review*, Dec. 1914, Vol. 42, p. 655, Washington.

[2] Hann, J.—*Lehrbuch der Meteorologie*, pp. 54 and 56, Leipzig, 1906.

tion of the solar heat by the air itself. The amount of the daily change, 2.9° F. or 1.6° C. almost on the equator, shows how much the air is heated by the direct rays of the sun during the day and cooled by radiation to space at night.

Records from self-recording instruments sent aloft on kites and



The Daily Period of Temperature at Different Heights in the Atmosphere

balloons have shown that the large daily change in the temperature of the air which is so marked a feature over land is confined to the stratum of air within a few hundred yards of the earth's surface. Fig. 44 gives a plot of the temperature at different heights observed every two hours at Blue Hill Observatory,[3] near Boston, latitude 42° 13′ N., longitude 71° 7′ E.

[3] Clayton, H. H.—*Nature,* Vol. 79, p. 397, London, February 4, 1909.

The numbers at the side show the deviation from the mean of the day. The curves in this figure show that the temperature in a shallow valley near the base of the hill, 50 feet (15 m.) above sea level, has a large daily range, rising from 8° F. below the daily mean at 8 A. M. to 8° F. above at two hours after noon. At a height of less than 2000 feet (600 m.) in the free air this variation has almost entirely disappeared, as is shown by plots of the observed temperatures at 500 and 1000 meters. Observations at Hald,[4] Denmark, show similar results, while the observations at Mount Weather,[5] Virginia, 39° 4′ N., 77° 55′ W., show that the daily period extends to a somewhat greater height, there being a small daily variation at 5000 feet (1500 m.) as seen in Fig. 50, in which are plotted the daily change at Washington, 112 feet above sea level, at the summit of Mount Weather, 1726 feet (526 m.), and in the free air at a height of about 5000 feet (1500 m.). In these and the following figures the exact heights are given in meters and approximate heights in feet.

In marked contrast with the decreasing temperature range in the free air with increased height above sea level, there is an increase in the daily range, when there is a large land surface at high levels to absorb and radiate heat. In Fig. 45 are plotted the variations from the daily mean at Mollendo,[6] Peru, a seacoast station, and at Cuzco, on an elevated plateau, 12° 31′ S., 72° 3′ W., and about 11,500 feet (3450 m.) above sea level. On these elevated plateaus the sun shines with a fierce intensity unknown at sea level, and the land and overlying air are greatly heated; while at night the loss of heat by radiation is equally great, so that the daily ranges of temperature at some of these elevated plateau stations are the greatest known in the world.

The daily changes of temperature in the free air, though small, have some very interesting characteristics which are illustrated in Figs. 46 and 47. These figures show the daily changes at different heights plotted on a larger vertical scale than that used in Figs. 44 and 50. In Fig. 47 the daily changes are shown for the level of 1000 meters (3300 feet) at Blue Hill, Massachusetts, for the level of 1343 meters (4470 feet) at Ben Nevis, Scotland, and for the level of 1500 meters (5000 feet) at Mount Weather, Virginia. The results for Ben Nevis were taken from the table

[4] Wundt, W.—*Meteorologische Zeitschrift*, 1908, pp. 337–341.
[5] Blair, W. R.—*Bulletins of Mount Weather Observatory*, Vols. 4 and 5, Parts 1 and 2.
[6] Baily, S. J.—*Annals of the Astronomical Observatory of Harvard College*, Vol. 49, Part 2.

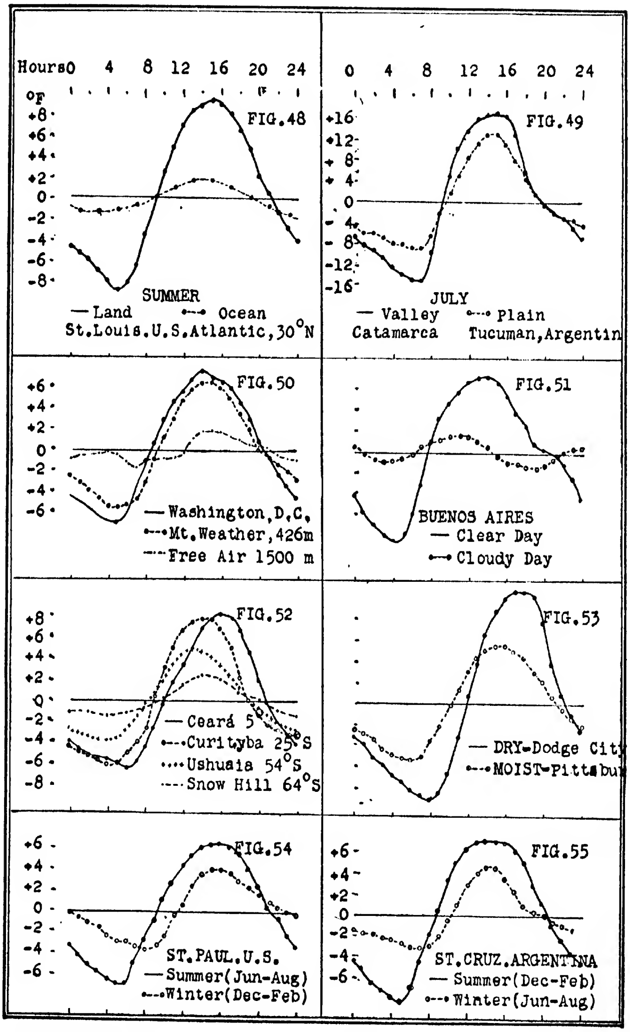
of J. Y. Buchanan,[7] showing the daily changes in temperature on the mountain in foggy weather when the summit is shaded from the sun by a stratum of cloud or fog, while at the same time the sun is frequently shining over the neighboring lowlands. The three curves in this figure show a striking similarity, (1) in *that there is a small maximum of temperature in the early afternoon when the temperature rises about one degree Fahrenheit above the mean of the day, (2) in that there is a secondary maximum at night between 2 and 4* A. M., *and (3) in that there is a minimum one or two hours after sunrise.* In Fig. 46 the daily changes are plotted for the level of 1500 meters (5000 ft.) above Blue Hill and for the levels of 2000 meters (6700 ft.) and 3000 meters (10,000 ft.) above Mount Weather. The plot shows that the temperature at 1500 meters at Blue Hill and 2000 meters at Mount Weather has a maximum at night and a minimum in the afternoon. This afternoon minimum is, I believe, due to the ascending currents which rise from the heated surface below. As explained previously, the air rising from the earth's surface cools by expansion at a rate which soon makes it as cool as the air at a few hundred yards above the surface; but, as the air has little friction, the ascending body of air passes beyond its point of equilibrium, until it actually becomes cooler and heavier than air of the same level, when it is either mixed with air at that level, or else sinks back to a plane of equilibrium. In this way, the air is chilled at successively higher levels during the day, until the ascending currents reach the levels of about 2000 meters in the afternoon. This super chilling explains, I think, the minimum at 1000 to 2000 meters in the day, and also explains the fact that the air in the tops of the cumulus clouds is usually colder than air at the same level. The heating at the surface furnishes the energy for the cooling aloft, just as the heat of a steam engine furnishes the energy for compressing the gases, the expansion of which produces the low temperature used in the manufacture of ice. At 3000 meters (10,000 ft.) the lowest temperature is found at night and the warmest in the afternoon, the daily range being about 2° F. or about the same as that found in midocean. The air at this level is rarely disturbed by local convection currents ascending from the earth's surface; hence, the daily heating must be due to the direct heating of the air by the solar rays by day in excess of terrestrial radiation and the cooling of the air at night by unchecked radiation to space. This

[7] Buchanan, J. Y.—"The Meteorology of Ben Nevis in Clear and Foggy Weather," July 1899.

small daily heating and cooling probably occurs throughout the atmosphere, one of the results of which is the daily change in temperature over the sea. Analyzing mathematically (see Appendix C) observations of temperature obtained with kites and balloons at Drexel, Nebraska, Dines[8] found the daily maximum of temperature at the ground (396 m.) to occur at 3:30 P. M., with a mean difference between maximum and minimum of 17.6° F.; while at 1500 meters (5000 ft.) the maximum occurred in the night (8:30 P. M.) with a daily range between maximum and minimum of 2.8° F. At 3000 meters (10,000 ft.) the maximum was again found in the afternoon at 4:30 P. M. and the daily range was 2.6° F. By a similar mathematical analysis Gold[9] found, from the temperature records obtained with balloons at Lindenburg, Germany, a daily range of temperature of 3.2° F. at 1000 meters and 2.2° F. at 2000 meters with maximum at both levels in the afternoon. The mathematical (harmonic) analysis shows smaller ranges for the half-day period at all the stations, the range being about 0.4° F. at 1000 meters above Blue Hill, 1.5° F. at 1000 meters above Drexel, and 1.5° at 1500 meters above Mount Weather, with maxima at all stations between 3 and 6 A. M. and P. M.

In Fig. 48 the daily changes of temperature for the summer months at St. Louis are compared with the daily change of temperature for summer over the mid-Atlantic about 30° N. From this plot the large daily range over the land and the small daily range over the water is distinctly evident. The form of the earth's surface also has a marked effect on the amount of the daily change. On mountain peaks the daily range is less than on plateaus at the same height. In valleys where the air is heated, not only by contact with the ground but also by reflected heat from the valley sides, the daily range is greater than over plains or slopes at the same height above sea level. Fig. 49 shows the daily range at Tucuman on a level plain and at Catamarca located in an open valley. Both stations are in northwestern Argentina. In the free air the daily range rapidly decreases with increased altitude above the surface as shown in Fig. 50. The daily change is also much greater on cloudy days than on clear days, as illustrated by Fig. 51, where the daily temperature changes at Buenos Aires for October 28 and 29, 1920, are shown. The readings were taken from the thermograph record of the

[8] Dines, W. H.—*Quarterly Journal of the Royal Meteor. Soc.*, Vol. 45, No. 89, p. 41, London, January 1919.
[9] Gold, E.—*Nature*, Vol. 81, p. 6. London, July 1909.



The Daily Period in Temperature Near the Earth's Surface Under Different Condition

central office of the Oficina Meteorológica and corrected for the difference between the beginning and end of the day. On October 28 the day was cloudless, except for a few broken cumulus clouds during the afternoon, and the large temperature range is shown by the continuous line in Fig. 51. On October 29 the sky was covered with a dense canopy of clouds and the small daily range is illustrated by the broken curve which up to noon showed a daily variation no greater than that observed over the open sea. In the afternoon light rain fell and the curve shows the fall of temperature which accompanies rain bringing down with it the temperature of a higher stratum. The decreasing daily range of air temperature over land surfaces at increasing distance from the equator is shown in Fig. 52. The stations are all in the southern hemisphere, Quixeramobim, Ceará, at which the daily change is shown by the continuous curve in Fig. 52, is in the equatorial zone, 5° 16′ S., 39° 56′ W.; Curityba, illustrated by the dotted curve, is a subtropical station in 25° 26′ S., 49° 15′ W.; Ushuaia, illustrated by the curve of crosses, is in the colder part of the temperate zone, 54°, 50′ S., 68° 20′ W., and Snow Hill, illustrated by the broken curve, is on the Antarctic continent, in 64° 21′ S., 56° 59′ W. The difference in the daily range of temperature in regions where the climate is moist and where it is dry is shown in Fig. 53 by a comparison of the mean daily changes at Pittsburgh and Dodge City in the United States, both inland stations near the same latitude. The greater daily range in the drier climate of Dodge City is shown by the continuous curve, and the smaller range at Pittsburgh by the dotted curve. The curves in Figs. 52 and 53 illustrate another phenomenon of importance, namely, that when the daily range is large there is a greater delay in the hours of occurrence of the maximum and minimum. At Quixeramobim, Ceará, the maximum and minimum occur about two hours later than at Snow Hill and Ushuaia, and at Dodge City from one to two hours later than at Pittsburgh. This delay is also visible in the curves of Fig. 48, but does not apply to the temperature in the free air shown in Fig. 50, where the temperatures of the upper level are dependent on those below and tend to follow a little later. The difference in the daily ranges between summer and winter for both the northern and the southern hemispheres are shown in Figs. 54 and 55. The curves for the two hemispheres are essentially alike, although the seasons are opposed, the summer of one hemisphere corresponding with the winter of the other.

These various diagrams bring out clearly that the daily change

in temperature over the globe is chiefly due to the heating of the land surfaces and is confined in large part to the stratum of air within about 3000 feet (900 m.) of the surface. It is greatest in the equatorial regions, where the sun shines nearly vertically overhead at noon, and least in the polar regions. It is large when the sky is clear, and small when there are dense clouds. It is greater in summer than in winter, and the maximum lags more behind the noon passage of the sun when the daily range is large than when it is small. When there is greater intensity of solar action, more time is needed for the full effect to be accumulated.

The daily range is also influenced by the character of the soil. The surface temperatures of different substances in sunlight observed by Th. Homen in Finland are quoted by Dr. Hann.[10]

	Granite	*Sand*	*Meadow*
Mean	23.0° C.	20.8° C.	16.4° C.
Maximum	34.8	42.3	27.7
Minimum	14.5	7.8	6.3

Surfaces covered with sand show the greatest daily range and over sandy plains the air temperature has a much greater daily amplitude than over grassy meadows.

But in addition to the daily change of temperature, due to the heating of the earth's surface, there is also a daily change of two or three degrees Fahrenheit, due to the direct absorption of heat by the atmosphere. In the upper air and over the ocean, all of the daily change is due to this cause.

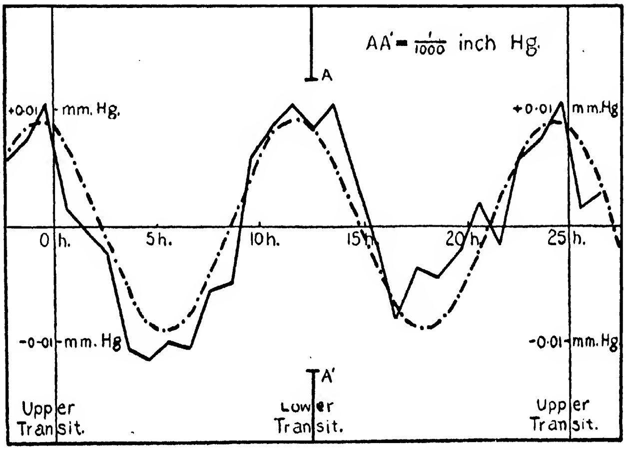
THE DAILY PERIOD IN ATMOSPHERIC PRESSURE

As previously stated, there is a slight daily tide in the atmosphere due to the attraction of the moon which S. Chapman[11] has been able to show by averaging thousands of observations at Greenwich. This daily wave, as seen in Fig. 56, shows two maxima in a period somewhat longer than a solar day on account of the movement of the moon in its orbit. The total range from maximum to minimum is only about one thousandth of an inch, as shown by the distance *AA′*.

There is a much larger daily change in pressure which coincides with the movements of the sun and is evidently caused by it. In the tropics it has a range from a maximum to minimum of about ninety thousandths of an inch and hence is ninety times

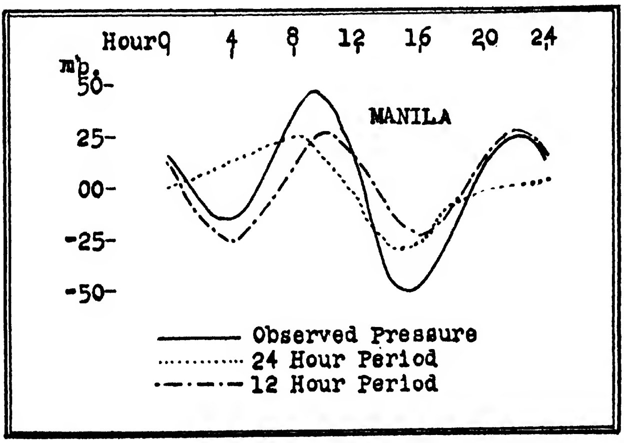
[10] Hann, J.—*Lehrbuch der Meteorologie*, p. 40, Leipzig, 1906.
[11] Chapman, S.—*Quarterly Jour. of the Royal Met. Soc.*, October, 1918, p. 271.

Fig. 56



Lunar Semi-diurnal Tide at Greenwich—After S. Chapman

Fig. 57



Daily Period of Pressure

as great as the lunar atmospheric tide. It also has two maxima and minima of unequal intensity in each twenty-four hours. Hann [12] and Angot [13] have shown that the daily change in pressure really consists of two periods, one having a single daily maximum and minimum in twenty-four hours and the other having a maximum and minimum each twelve hours. The twenty-four-hourly, or whole-day, period is closely related to the surface temperature and changes with changing conditions in the same way, while the twelve-hour period is independent of surface conditions.

Fig. 57 shows the observed daily pressure change at Manila, Philippine Islands, for January, analyzed into two periods, a whole-day and a half-day period, by Rev. Antona Galan,[14] S. J., by means of Angot's formula. It is usual to analyze the observed changes into two periods by the harmonic formula (see Appendix C), but Angot's formula gives a more accurate analysis because it takes into account the causes controlling them. The whole day, or twenty-four-hour period, he calls the "thermic wave" because it depends on the familiar daily change of temperature in the lower strata of the atmosphere.

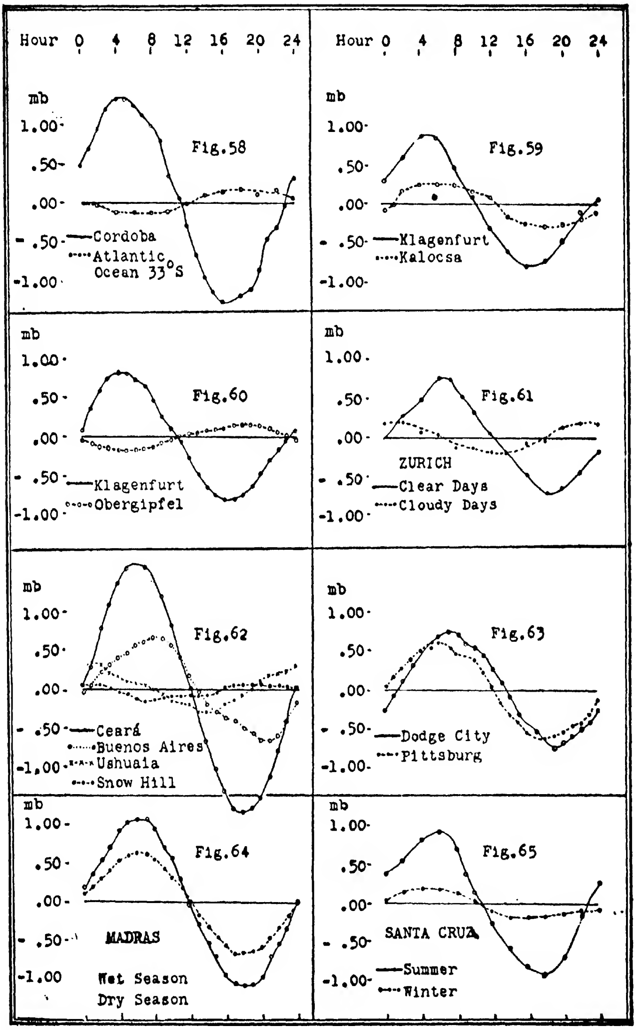
In separating the two waves for study, I have followed the simple process of averaging the departures from the daily mean pressure for each hour of the twelve-hour period, which thus gives the half-day period, and then subtracting these means from the means of the observed pressure for each of the twenty-four hours to obtain the twenty-four-hour period freed from the twelve-hour changes. These values are approximately the same as would be obtained by harmonic analysis.

The daily period obtained for different parts of the world and under different conditions are shown in Figs. 58 to 65, and it is seen that the trend of the daily wave is inverted to that of temperature, the pressure being high when the temperature is low, and low when the temperature is high. It is also evident that the amount of the change varies much in the same way as the daily change in temperature. At a mid-continental station, like Cordoba, in central Argentina (see Fig. 58), the change is large, while over mid-Atlantic, 33° S., it is small and inverted. Almost

[12] Hann, J.—"Untersuchungen über den täglichen Gang des Barometers," Wien, 1889.

[13] Angot, A. M.—*Annales du Bureau Centrale Meteorologique de France* 1887, p. B297, Paris.

[14] Galan, Rev. Antona, S. J.—"The Harmonic Formula of Fourier and Bessel and Its Application to the Study of the Diurnal Variations of the Atmospheric Pressure in Manilla during the Period 1890–1909." *Manila Observatory,* 1914.

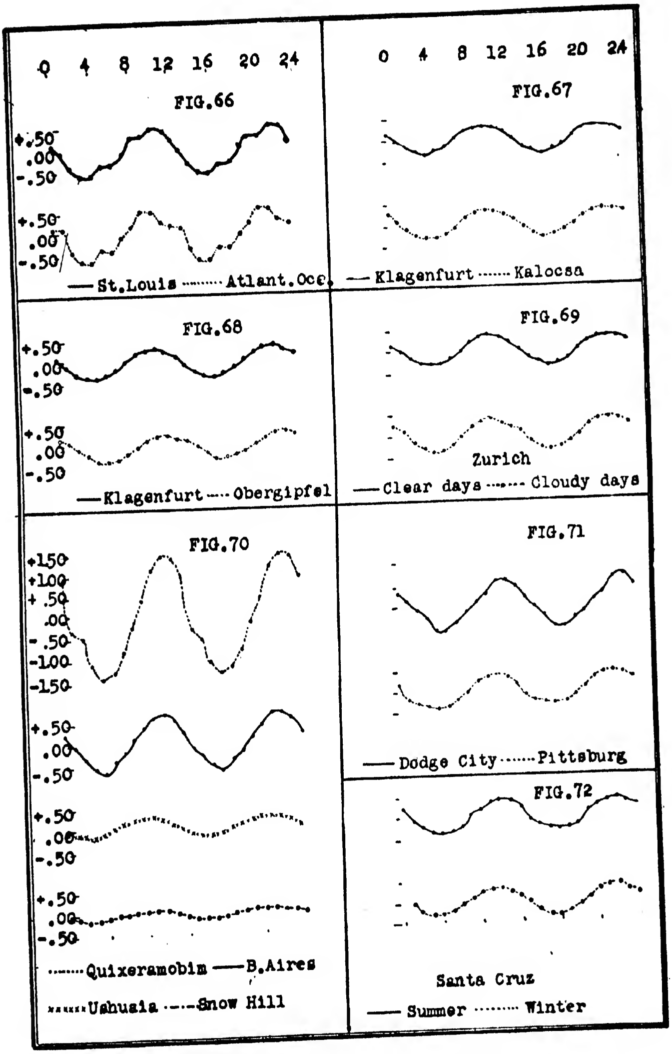


Whole Day Period of Pressure under Different Conditions

exactly the same form of curve is obtained for St. Louis, a mid-continental station in the United States, and for the mid-Atlantic at 30° N. Fig. 59 shows that the daily range is much larger at Klagenfurt, a valley station in northern Europe, than at Kalocsa, a station in more open country. Fig. 60, comparing the whole-day pressure change for the summit of the Obergipfel in Germany with Klagenfurt near its base, shows that the change decreases with increase of height above the earth's surface and is inverted at no very great altitude (6700 ft.). This inversion is found on every mountain summit where observations have been taken. Fig. 61 shows the daily change of pressure on clear and cloudy days in Zurich. The pressure change is much less on cloudy than on clear days and the maximum is nearer midnight.

The whole-day change of pressure also decreases rapidly with increase of latitude of land stations, as is evident from Fig. 62, which shows the changes of pressure at a series of stations near the coast of the South American continent. At Quixeramobim, Ceará, Brazil, in the equatorial zone, 5° S., the diurnal range is very large; at Buenos Aires, in the temperate zone, 34° S., it is only about half as great; while at Ushuaia, 55° S., it is only about one fifth as great. At Snow Hill, on the antarctic continent, 64° S., it has become very small and is inverted probably for the same reason that it is inverted over the oceans, namely, that the air is thrust south by lateral expansion over the equatorial land masses and increases the pressure in Arctic and Antarctic stations during the warmest part of the day (see Fig. 4). Comparing the daily pressure wave at Dodge City with that at Pittsburgh in Fig. 63, it is found that the daily change is greater in dry climates than in wet climates; comparing the daily changes at Madras during the wet and dry season, shown in Fig. 64, the greatest range is found in the dry season; and, comparing the daily change in summer with that in winter, as in Fig. 65, the greatest range is found in summer, when the sun is most nearly vertical at noon. Comparing these whole-day pressure changes with the temperature changes under similar conditions, it is apparent that the intensity of the pressure changes varies in the same way under similar conditions as does the daily temperature wave, and there can scarcely be a doubt that the daily changes of temperature bring about the daily changes of pressure.

Plots of the half-day, or twelve-hour period, of pressure are given in Figs. 66 to 72. Fig. 66 shows that the amount of the



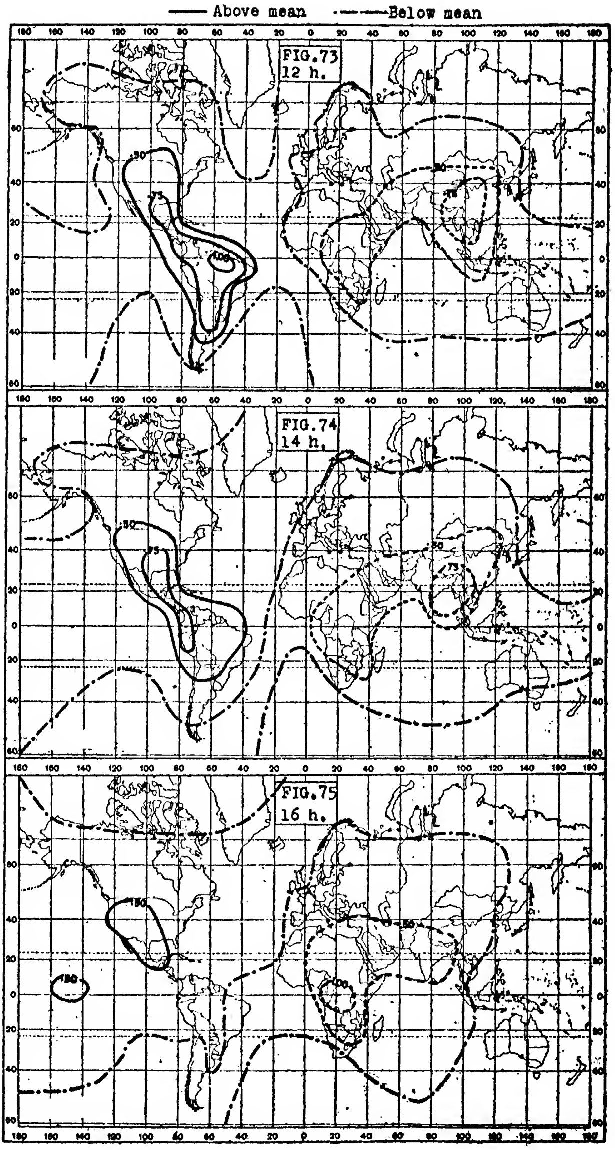
The Half-day Period in Pressure under Different Conditions

oscillation is just as great over the ocean as over the land. Fig. 67 shows that it is as great over plains as over valleys. Fig. 68 shows it to be similar at the top and base of a mountain, the only difference being a slightly decreased range which Hann has proved to be exactly proportional to the decreased mass of air. Fig. 69 shows that at Zurich it is just the same on clear as on cloudy days. Fig. 70, derived from the chain of stations in different latitudes in South America, shows that the form of the curve remains the same, but there is a diminishing amplitude in the oscillations with increasing latitude until at 64° S. it becomes quite small. Thus the amplitude is greatest where the noon sun is most nearly vertical. This conclusion is confirmed by Fig. 72, which shows that the amplitude of the oscillation is greater in summer than in winter.

From these comparisons, it is evident that the twelve-hour period of pressure is dependent on solar radiation, but is entirely independent of the condition of the earth's surface beneath the sun, whether it be land or water, plain or valley, or whether the land is in shadow or sunshine. The perfect symmetry of the wave indicates also that it is not dependent on local conditions, but is a phenomenon of the free air. It is probable that it arises from the direct absorption of solar heat by the air itself and its radiation into space at night.

Why there should be two maxima and minima each twenty-four hours is not so clear. The most accepted explanation is that it is a form of vibration in the air akin to the phenomenon of resonance. When musical sounds are made near a body having a special pitch or keynote, the sound waves corresponding to the keynote are absorbed and the body begins to vibrate in unison with that note. Lord Kelvin suggested that the atmosphere had a free swing of about a half day and that the unsymmetrical form of the daily change of temperature gave rise to a half-day period which set the atmosphere in vibration. The calculations made by Margules [15] are accepted by many meteorologists as a satisfactory solution of the problem along these lines. Lamb [16] also attributes the double diurnal waves to forced vibration but believes the cause to be in the daily convection currents of the lower atmosphere. The theory of two pressure waves each day traveling from east to west, with the largest amplitude at the equator and vanishing to zero at the poles, does

[15] Margules, M.—"Uber die Schwingungen Periodischer Erwärmten Luft," Wien, 1890, pp. 204–227.
[16] Lamb, H.—*Proc. Royal Society,* V. 84-A, p. 551 (London, 1911).



Bihourly Charts of the Whole Day Pressure Wave

not fully explain the times of occurrence nor the amplitudes observed at stations near the poles. Hence, Simpson [17] has suggested an additional half-day oscillation which moves from equator to poles. He computes the amplitude of this oscillation to be about one seventh of the amplitude of the east to west traveling wave.

Such explanations of the half-day period as those which involve rapidly rising temperatures during the morning hours or the action of convection currents at the place of observation cannot be considered as causes in the light of the fact that this half-day wave is well developed over the vast stretches of the south Pacific, where there is little change in the daily temperature and where daily convection currents, if they exist at all, are extremely weak. The half-day wave of pressure is evidently a phenomenon of the free air in which the whole atmosphere is involved.

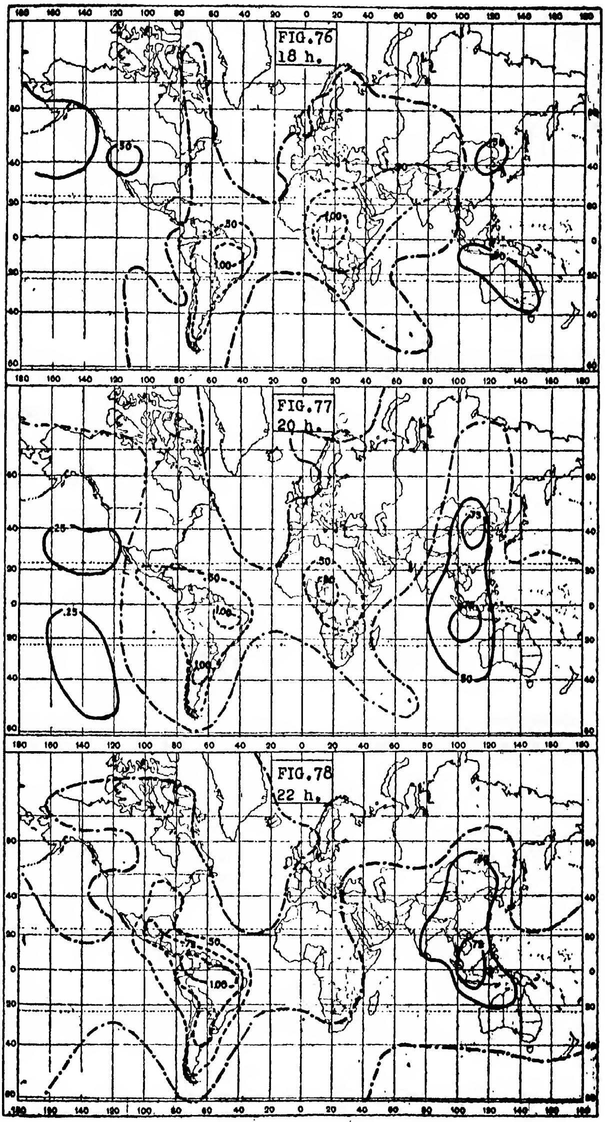
The dependence of this wave on the direct action of solar energy is not only evident from the fact that it is most developed where the sun is most nearly vertical, but also by the fact that there is a variation of the intensity in the tropics proportional to the distance of the sun from the earth.

On account of the elliptical orbit of the earth, the sun is nearly seven per cent of its mean distance nearer the earth in December than in June and there is a corresponding variation of seven per cent in the intensity of the half-day period near the equator, as has been shown by Hann.[18] The half-day wave of pressure change also shows a semiannual change, due probably to the greater effectiveness of the rhythmic action of solar heat and atmospheric radiation when the days and nights are nearly equal, as the largest daily amplitudes are found in March and September, when the sun is on the equinox and the smallest in June and December.

In order to study the progress of the pressure waves around the world, the mean daily changes in pressure for 181 stations scattered over the globe were analyzed into whole-day and half-day waves and were reduced to Greenwich time. The departures from the mean of the day for each hour, Greenwich time, were then plotted on charts for both the whole-day and half-day periods. Charts of the whole-day period are reproduced in

[17] Simpson, G. C.—*British Antarctic Expedition, 1910–1913,* Meteorology, Vol. 1, pp. 182–183, Calcutta, 1919. Also *Quarterly Journal of the Royal Meteorological Society,* Vol. 44, No. 185, p. 1, London, 1918.

[18] Hann, J.—"Untersuchungen über den täglichen Gang des Barometers," Wien, 1889.



Bihourly Charts of the Whole Day Pressure Wave

Figs. 73 to 78, showing the departure for each two hours from noon to 10 P. M. (12 h. to 22 h.). Lines are drawn for departures from the daily means for 10, 50 and 100, the units being hundredths of a millibar. The plus departures are indicated by full lines, and the minus departures by broken lines. Examining Fig. 73, it is seen that over a large part of Asia and Africa at Greenwich noon the pressure is below the daily mean and is especially low over the tropical land surfaces where the deficiency exceeds 0.50 millibar. Over the Americas the daily pressure is above the daily mean, especially over the equatorial part of South America, where it exceeds 1.00 millibar. Another interesting fact to be noticed is that, while the pressure is below the daily mean in the tropical and temperate regions of Asia, it is above the daily mean near the Arctic Circle and also at points south of 40° S. On the other hand, it is below the daily mean in the Arctic and Antarctic to the north and south of the Americas. It is also above the daily mean over the oceans east and west of Asia-Africa and below the mean over the oceans east and west of the Americas north and south of about latitude 20°.

Fig. 74, giving conditions two hours later, that is, at 14 hours, Greenwich time, shows very little change except that the pressure has deepened over Africa. At 16 hours the highest pressure is found over the United States and the lowest over Africa. At 18 hours low pressure is found over South America and eastern North America, as well as over Europe and Africa, while the highest pressure is in western Asia and the pressure is above the mean over the oceans. At 22 hours the lowest pressure is over the Americas, and especially over equatorial South America, where the depression exceeds 1.00 millibar. The highest pressure is over Asia, while the pressure to the north of 60° and south of 40° S. latitude is below the mean. It is seen that the greatest departures are always over the tropical or semi-tropical land masses, and as the sun moves from east to west the departures jump from one continent to the next most favorable land mass. The low pressure over Asia, Europe and Africa seen in Figs. 73 and 74 corresponds to the warmest part of the day in these continents. No doubt, the air is expanded both vertically and laterally at this time by the heat as illustrated in Fig. 4. The vertical expansion is attested by the rise of pressure on the mountain tops as shown by observations on mountains in India, in Africa and in Europe. The lateral expansion is evident from the rise in pressure in the Arctic and Antarctic regions as well as over the oceans of temperate latitudes. That the expansion

of air over the continental land masses can cause pressure changes within a few hours at widely distant parts of the earth, is a matter of the greatest interest in studying the influence of solar heat changes. On the other hand, the contraction of the air by the cold causes the pressure to rise over the continental masses and to fall over the ocean and Arctic and Antarctic regions.

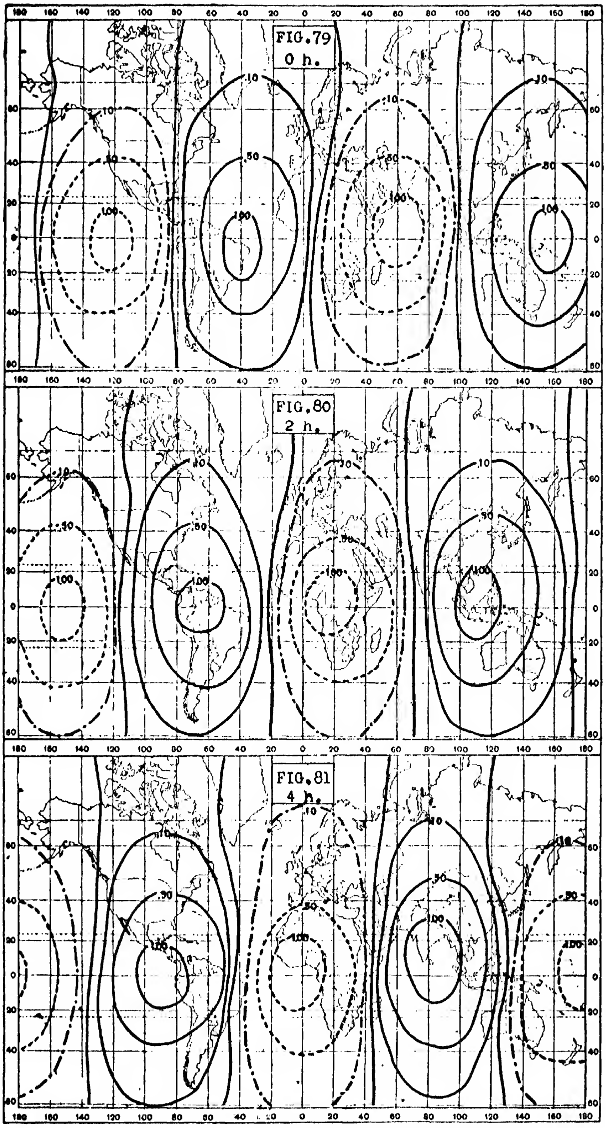
When one turns to the plots of the departures from the mean of the twelve-hour, or half-day, period shown in Figs. 79 to 84, an entirely different phenomenon is seen. Here the half-day pressure waves sweep from east to west following the sun and return each day to the same point, almost with the regularity of the beats of a pendulum.

There are four centers of greatest departure almost exactly on the equator and about ninety degrees apart, two centers of high and two centers of low pressure. The pressure center over the Indian Ocean appears to be drawn slightly northward by the land mass of Asia, and that over the Atlantic slightly southward over the land mass of Brazil, but this may be only apparent and due to insufficient observations over the ocean or else to the method of reduction. The lines of equal departure for 10, 50 and 100 measured in hundredth of a millibar as unit are very symmetrical. Between 20° N. and 20° S. the ranges exceed 1.00 millibar, between 40° N. and 40° S. they exceed 0.50 and between 60° N. and 60° S. they exceed 0.10, while near the poles they have apparently the same phases as at lower latitudes, but the ranges are very small. Following the separate centers from chart to chart, we see that they progress westward about thirty degrees each two hours, passing half around the world in twelve hours or entirely around in twenty-four hours. The first chart, Fig. 79, is for Greenwich noon. The high pressure will be about two hours in advance of the sun and the low about four hours behind and they maintain this relation, so that the high occurs at every place on the Globe about 10 A. M. and the low about 4 P. M. local time; the second high and low follow twelve hours later in the same order.

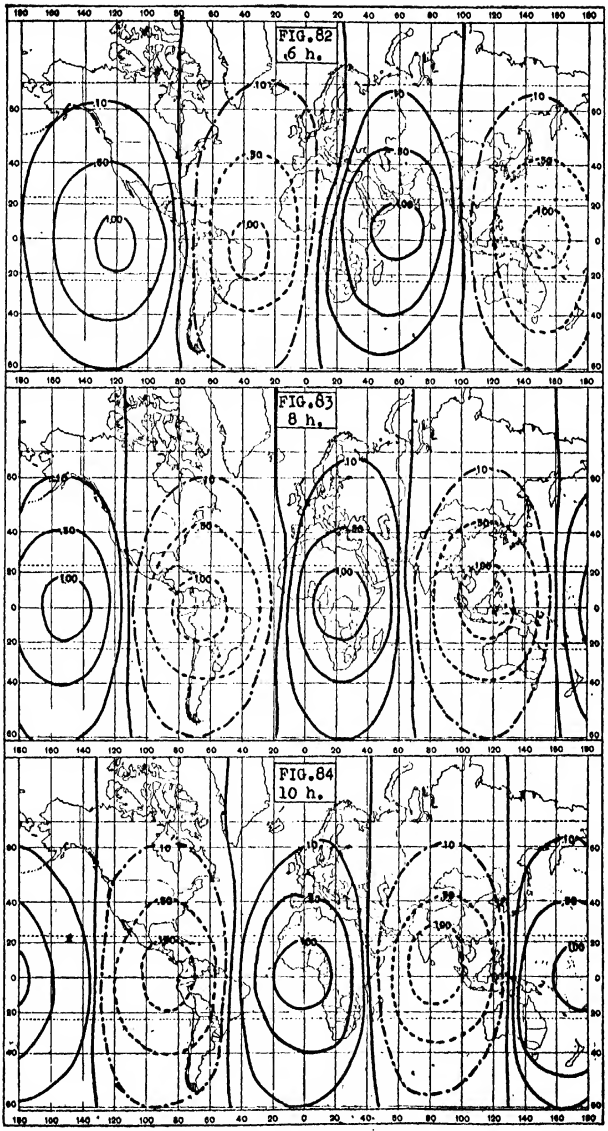
The centers of greatest amplitude move north and south with the sun so that they are found north of the equator from April to August and south of the equator from October to February.

THE DAILY PERIOD IN THE WINDS

The tendency of the winds to blow from cooler water surfaces by day toward the heated land, and from the cooler land by night



Bihourly Charts of the Half-day Pressure Wave



Bihourly Charts of the Half-day Pressure Wave

toward the warmer water, and also the tendency for the wind to flow up the valleys and heated sides of the mountains by day and down at night, were referred to previously under the heading of sea and land breezes and valley and mountain breezes, respectively. These tendencies to a forward and backward movement by day and night are strengthened by certain local conditions. When there is an elevated sandy plateau or a snow-covered slope near sea level, the night winds toward the sea become exceptionally strong.

Air currents blowing outward from the lower end of a glacier have so often been observed that they have received the name of glacier winds. This class of winds is especially accentuated around Greenland and the Antarctic continent, both of which are covered with a perpetual ice-sheet, around which are observed almost continuous aërial cascades and windfalls, stronger at night than by day.

Another cause of the daily changes in the wind over land areas is the heating of the surface during the day, causing the lower air to be replaced by air from a higher level which is moving with a greater velocity. This descending air brings its velocity down with it, and causes the afternoon winds, usually, to be the strongest of the day; while the reverse is the case at a level of a few thousand feet, near the top of the ascending currents. J. Durward has summarized, in "Professional Notes" No. 15 of the Meteorological Office (London, 1921), the recent studies of the diurnal period from observations with pilot balloons liberated at regular intervals of a few hours during the World War. At the earth's surface there is a marked increase of wind during the day, while at 1000 to 2000 feet in the free air there is a marked decrease. At 3000 feet the decrease is less and does not appear at all in winds from south and east. Observations on the Eiffel Tower (1000 ft.) also show that there is a reversal of the daily change of velocity observed at the earth's surface. There are also slight changes of directions at the different levels resulting from the daily changes of velocity as was shown by Sprung.[19] At night, when the surface air is chilled, there is a decreased wind velocity and, where the earth's surface is uneven, the movement of the air is so retarded by friction that calms are frequent.

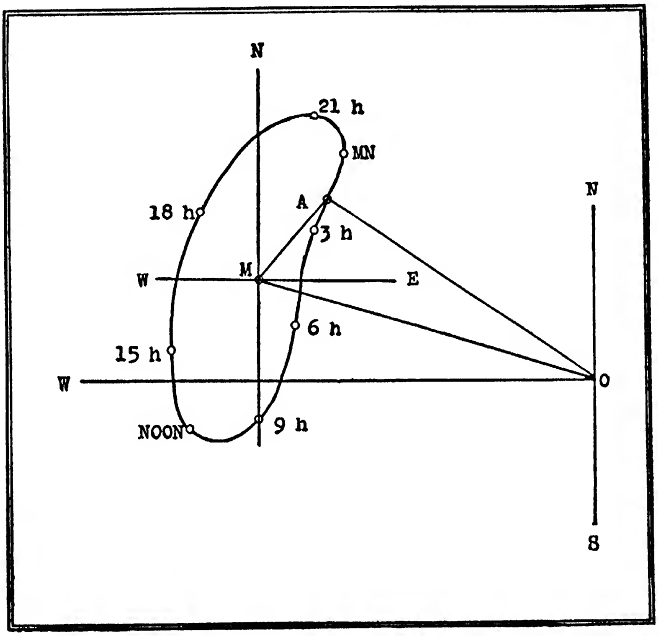
The cause of this daily change of velocity was first given by Espy, and confirmed by the researches of Köppen. G. I. Taylor has recently shown that the eddying of the air, set up by the mingling of currents of different velocities, also plays an im-

[19] Sprung, A.—*Lehrbuch der Meteorologie*, p. 345, 1885.

portant part in it by retarding the motion of the air in proportion to the amount of eddying.

Another condition was disclosed by the observations obtained with kites at Blue Hill, Massachusetts, namely, that the wind above the retarded currents near the ground not only resumes its normal velocity at 1600 feet (500 m.) at night, but is greater

Fig. 85



Daily Components of the Wind on the Eiffel Tower, Paris

than that immediately above it; while during the day it is also greater above the top of the ascending currents than at somewhat higher levels. These increased velocities probably arise from the tendency of the air to preserve a continuity of flow, so that the wind increases above quiet air just as it does over a mountain ridge, or as water increases its velocity of flow over a dam or other obstruction to a steady, uniform flow.

In addition to the daily changes in the wind already described, there are the winds accompanying the barometric waves. The

whole-day barometric wave has its maximum at night and its minimum in the afternoon over the land in every part of the world. The wind everywhere is known to oscillate about its mean position during the course of the day and, if the mean direction is eliminated, the resultant or vector winds show daily changes very clearly related to the daily barometric waves. In Fig. 85, which shows the mean winds at the Eiffel Tower, let *MO* represent the mean wind for the twenty-four hours (from *WNW*) and *AO* the mean wind at 2 A. M., then *MA* represents the vector wind or the wind which acting on *MO* would change its direction from a *WNW* to a *NW* wind as represented by *AO*.

TABLE II

WIND FREQUENCIES

Blue Hill — 42° 13′ N., 71° 7′ W.									Cordoba — 31° 25′ S., 64° 12′ W.								
	N	NE	E	SE	S	SW	W	NW		N	NE	E	SE	S	SW	W	NW
3 A.M.	17	19	6	11	22	**12**	2	11	3 A.M.	16	8	5	6	8	16	20	21
6 "	16	17	6	11	**27**	12	0	11	6 "	**16**	9	5	6	8	16	18	22
9 "	**20**	26	4	14	24	7	0	5	9 "	13	10	6	7	9	15	16	24
12 "	17	34	7	16	21	3	0	2	12 "	8	**13**	6	5	9	15	17	**27**
3 P.M.	15	35	11	**19**	15	2	0	3	3 P.M.	6	11	**9**	7	10	14	18	25
6 "	10	**36**	**14**	18	16	3	1	2	6 "	10	7	7	**11**	14	15	13	22
9 "	16	26	8	15	19	7	1	7	9 "	11	6	4	9	**15**	**20**	15	20
12 "	18	21	6	12	22	9	1	11	12 "	14	6	4	6	10	19	**21**	20

By following the vector winds from hour to hour, it is seen that they progress around the compass in the same direction as the hands of a watch. The reverse is the case in the southern hemisphere. This difference can be seen by comparing the frequency of each wind from hour to hour. In Table II the wind frequencies are given for intervals of three hours at Blue Hill [20] in the northern hemisphere and at Cordoba in the southern hemisphere. The maximum frequency of each wind is marked with heavy type and the reverse direction of the progress of the maxima is easily followed.

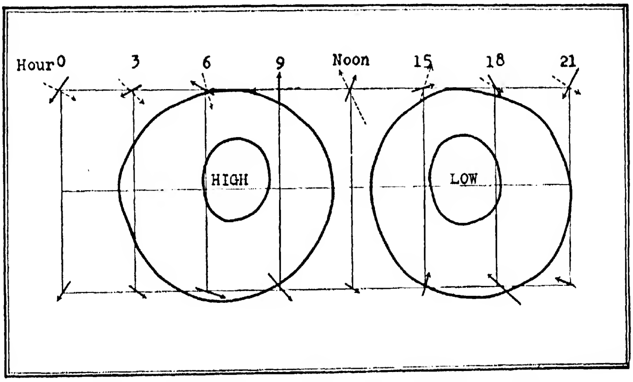
In Fig. 86 the full arrows at the top of the diagram represent the resultant or vector wind direction and velocity from observations on the Eiffel Tower in Paris derived from the results obtained by Angot.[21] The full arrows at the bottom of the diagram

[20] Clayton, H. H.—"Discussion of Cloud Observations," *Annals of the Astronomical Observatory of Harvard College,* Vol. 30, Part 4, Cambridge, Mass., 1896.

[21] Angot, A. M.—*Annales du Bureau Central Meteorologique de France Memoires de 1897,* p. 171.

show the wind vectors at Buenos Aires, as determined by Rankin,[22] for the months of August to November when the sea breeze is less developed than in summer. The length of the arrows in each case represents the velocity of the wind. Both north and south of the equatorial region there are found outflowing winds from the high pressure at night and inflowing winds into the low pressure of the afternoon, the winds of Buenos Aires being deflected by the earth's rotation into a southern-hemisphere circulation, but those at Paris do not show clearly a northern-

Fig. 86



Daily Wind Components in the Whole Day Pressure Wave

hemisphere circulation. The dotted arrows at the top of the diagram represent the direction and velocity of the wind on mountain summits in the northern hemisphere. These winds are the vector winds derived from the means of the observation on the Sonnblick, Santis, Obergipfel, and Pike's Peak.[23] They show clearly that the upper winds tend to flow into an area of high pressure at night to supply the air flowing out below, and to flow out in the afternoon to balance the inflow at lower levels. This circulation also accords with the low pressure found by night on mountain summits and the high pressure found by day. The circulation conforms to that of the northern hemisphere.

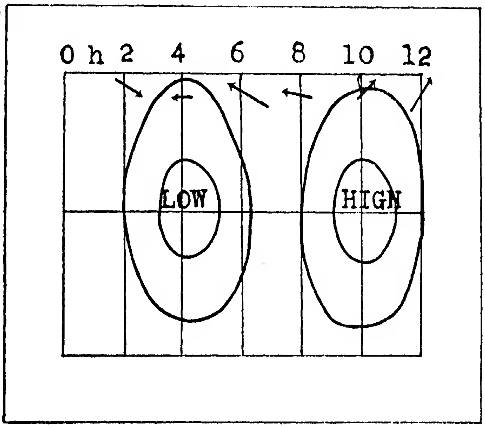
Besides these day and night changes in the wind, there is also a twelve-hour change, corresponding to the twelve-hour baro-

[22] Rankin, A.—"Los Vectores del Viento de Buenos Aires durante los Años, 1906–1913. *Boletin Mensual, Oficina Meteorológica,* Buenos Aires, 1921.
[23] Hann, J.—*Lehrbuch der Meteorologie,* p. 299, Leipzig, 1906.

metric wave. This change can be seen by averaging the wind in twelve-hour periods. The observations at the Blue Hill Observatory,[24] near Boston, are conveniently arranged for this purpose and the twelve-hour vector winds are shown in Fig. 87. These vectors show clearly a circulation about the low pressure which occurs at 4 A.M. and 4 P.M. and the high pressure which occurs at 10 A. M. and 10 P. M. The circulation conforms with the northern hemisphere circulation around highs and lows.

There are hence daily changes in the wind resulting from four distinct causes, namely:

FIG. 87



Relation of Winds to Half-day Pressure Wave

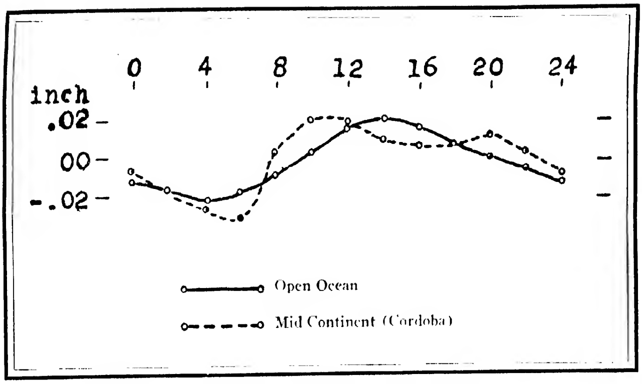
1. The sea and land, mountain and valley or other wind caused by local difference of temperature in adjacent areas.

2. The ascending and descending currents during the day caused by vertical instability bringing about changes of direction and velocity by the intermingling of different strata and the formation of eddies.

3. A daily rotation of the vector winds in the direction of watch hands in the northern hemisphere and in the opposite direction on the southern hemisphere, caused by the daily change in pressure.

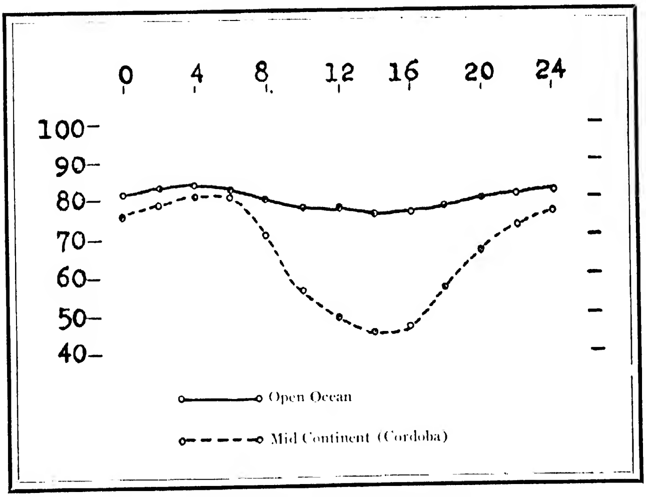
[24] Clayton, H. H.—"Discussion of Cloud Observations, *Annals of the Astronomical Observatory of Harvard College*, Vol. 30, Part 4, Cambridge, Mass., 1896.

Fig. 88



Daily period in Absolute Humidity

Fig. 89



Daily period in Relative Humidity

4. A twelve-hour rotation of the vector winds, making a figure of eight movements at any given point during the course of the day in opposite directions in the two hemispheres, caused by the semi-daily barometric wave.

THE DAILY PERIOD OF HUMIDITY, CLOUDS AND RAINFALL

The absolute amount of moisture in the air is usually lowest at night, when part of the moisture is deposited as dew, and highest in the day, when the higher temperature increases the water vapor in the air. Over the open ocean, as shown by the observations of the *Challenger Expedition,* the curve is a simple one, having a minimum at night and a maximum at the warmest time of the day (see Fig. 88); but over continents there are two minima, one at night, evidently due to the condensation of moisture by cold, and the other in the afternoon, due to the elevation of the surface air by ascending currents and its replacement by drier air from above.

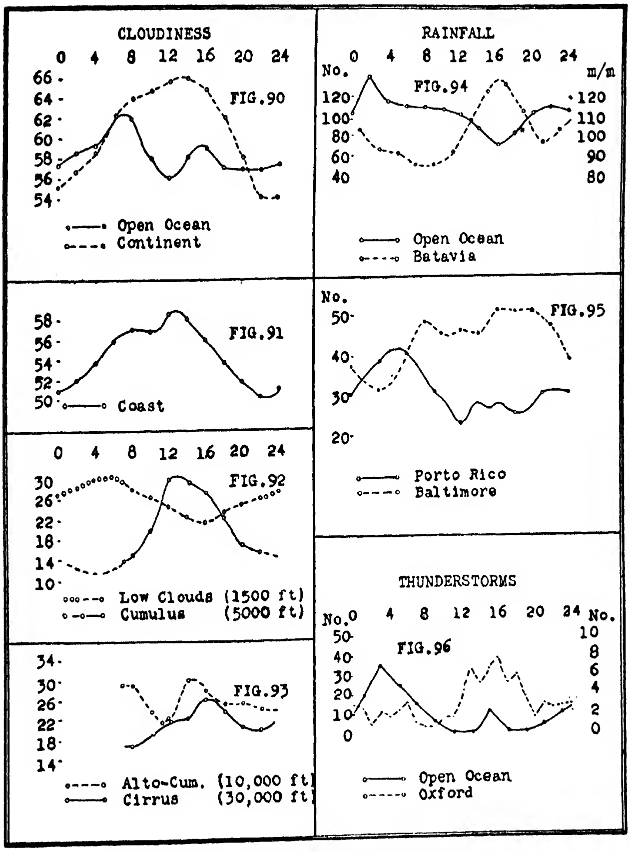
The relative humidity, as shown by Fig. 89, is higher over the ocean than over the land and the daily change is much less; but, over both land and water the change is opposite to that of the daily temperature change, and proportional to it in amount. The data for both the absolute and relative humidity over the land shown by dotted lines in Figs. 88 and 89 are taken from the observations at Cordoba published by W. G. Davis in "El Clima de la República Argentina," Buenos Aires, 1910.

The daily variation in the amount of clouds over the ocean and at a land station is shown in Fig. 90. The curve for the open ocean has a maximum at night and a secondary maximum in the afternoon. It is the form of daily change found at most stations in the world, even at some land stations, like Vienna; but at most land stations there is a minimum at night, like the dotted curve in Fig. 90 for Paris, which is made up of the means of the four months December and January and May and June, and the curve for Blue Hill in Fig. 91, showing the cloudiness at a coast station.

The observations made by me at Blue Hill Observatory, near Boston, show that the daily period in cloudiness in the lower air below 3000 feet has a maximum at night and a minimum by day (see dotted curve in Fig. 92); while between 3000 and 10,000 feet the humidity and amount of cloud have a marked maximum by day, due to the ascent of moist air from the earth's surface (see full curve in Fig. 92). Above 10,000 feet there are two

maxima and two minima each day, corresponding to the two maxima and minima in the pressure of the air (see Fig. 93).

The continuous curve in Fig. 94 shows the rainfall frequency



Daily Periods in Clouds, Rainfall and Thunderstorms

over the open ocean, and the dotted curve the rainfall at Batavia, a land station, as given in the report of the *Challenger Expedition.*

The curves indicate a maximum of rain in the night over the ocean and in the afternoon over the land. The daily period at

coast stations usually has two maxima, one at night and the other in the afternoon, with minima near noon and between 9 P. M. and midnight, while islands far from the mainland show the ocean type (see Fig. 95 by Fassig[25]).

The curve for thunderstorm frequency in Fig. 96 has the same characteristics as the rainfall with a maximum frequency at night over the ocean and in the afternoon over the land; but each curve shows a secondary maximum at the time of the chief maximum of the other curve. Since the overturning of air in a vertical direction and the cooling by expansion of moist air ascending from the earth's surface is known to be one of the causes of rain, and probably the chief cause of thunderstorms, there are thus seen to be two causes of vertical instability in the air, one the heating of the surface during the day, which takes place chiefly on land, and the other the cooling of the air aloft, probably brought about by radiation at night from clouds or saturated air. This latter is the chief cause of vertical instability and convectional overturning over the ocean and at many coast stations, especially in winter.

[25] Fassig, Oliver L.—*Second Pan American Scientific Congress* Proceedings, Vol. II, p. 463, Washington, 1917.

CHAPTER III

THE YEARLY PERIOD IN THE WEATHER

SUMMARY

As a result of the movement of the earth around the sun and the inclination of the earth's axis, there is an annual variation of the amount of radiant energy received from the sun at places on the earth's surfaces which causes annual changes in weather conditions. The amplitude of the temperature change in the annual period, although relatively large throughout the atmosphere, varies with the quality and the form of the earth's surfaces, being larger over the land than over the water, larger at the earth's surface than at great altitudes, and larger in the northern hemisphere than in the southern hemisphere.

In high latitudes the continents are hotter in summer than the oceans and are colder in winter. Greenland and the Antarctic Continent being covered with snow are exceptions. In low latitudes the continents are warmer than the oceans at all times of the year. As a result of these differences there are many centers of heat and cold in the atmosphere and the resulting differences of temperature bring about distributions of pressure, rains and clouds which vary with the season. Plots of pressure are given across the poles and across the oceans and continents in an east and west direction. The plots across the poles show that the pressure distribution retains the same form throughout the year, but the intensity and position of the maxima and minima change somewhat with the season. The plot across the continents and oceans at 50 degrees north latitude shows a complete inversion of the pressure between January and July, while a plot at 30 degrees south latitude shows only a partial inversion. In the north there are two maxima and two minima in the curves, corresponding to the two continents and two oceans, while in the south there are three maxima and three minima, corresponding to the three continents and oceans.

There is found a marked half-yearly period in the pressure which oscillates inversely at the 40th and at the 70th latitude. This half-yearly period is also found in the pressure gradient between South Georgia and the Orcadas in the South Atlantic and is noted in the winds in temperate and high latitude in both hemispheres.

It is believed to be due to increased intensity in the polar cyclones when the sun crosses the equator in March and September. There is a greater contrast in temperature between pole and equator when the sun is on the equator, and also a diminished contrast in temperature between the continents and the oceans of high latitudes, so that the general atmospheric circulation is less interrupted by convective interchange. For both these reasons the general atmospheric circulation becomes stronger at the Equinoxes. As a result of the increased atmospheric circulation the pressure rises near the 30th parallel and falls in high latitudes around the poles.

The maximum wind velocity in the half-year period occurs, in general, in March and September, as does also the maximum depression of pressure in the circles around the poles at about 70 degrees latitude.

The annual period of rain is closely related to the annual periods in the temperature and winds. It is also influenced by the configuration of the earth's surface, as regards the distribution of land and water and the interruption of the winds by mountains.

The data for the annual periods in clouds and moisture are not so numerous as for the other elements, but there is found to be a change in the range of the annual period dependent on latitude and a correlation with the distribution of continents and oceans.

As the spin of the earth on its axis brings the various configurations of the earth's surface beneath the solar rays each twenty-four hours, and thus gives rise to the various daily changes in the weather, so the annual pilgrimage of the earth around the sun causes the sun to swing backward and forward across the equator and exposes first one hemisphere and then the other to the direct solar rays. The change of the earth's position, as a result of which the height of the sun above the horizon at any place varies greatly during the year, causes large yearly changes in temperature and the many varied weather changes of the yearly period.

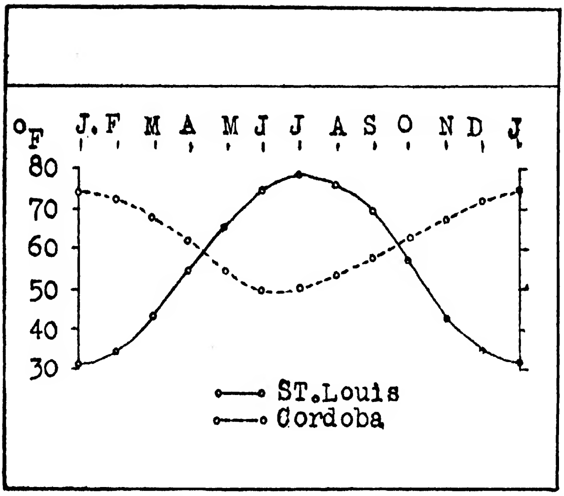
THE YEARLY PERIOD IN THE TEMPERATURE

The yearly change in temperature is more important than that of the other elements, because nearly the whole of human activity is adjusted to this annual change. In temperate and higher latitudes, the highest temperature is reached about a month after the summer solstice, when the noonday sun reaches its highest point in the heavens, and the coldest about a month after the winter solstice, when the sun is at its lowest point. But as the sun is lowest in the southern hemisphere when it is highest in the northern, the seasons are reversed.

Fig. 97 gives a diagram of the yearly changes at St. Louis, a continental station in the northern hemisphere, and at Cordoba, a continental station in the southern. It is seen that the highest temperature occurs at Cordoba in January, when the lowest occurs at St. Louis. The range is greater at St. Louis because the land surfaces of North America are larger than the land surfaces of South America.

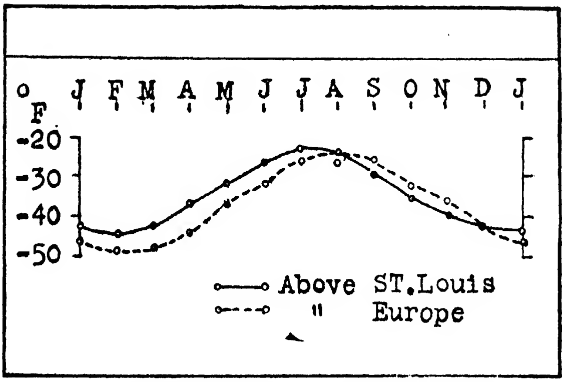
The annual period, although showing the largest range over continents near the surface of the earth, is not confined to the lower part of the atmosphere over land surfaces, as is the daily period, but extends to the highest part of the atmosphere, as high as it has been possible, up to the present, to obtain observations. It is also large over the oceans, because the length of the

FIG. 97



Yearly Period of Temperature in the Northern and the Southern Hemisphere

FIG. 98

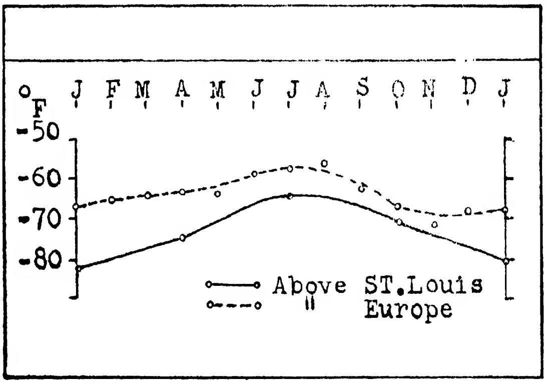


Yearly Period of Temperature at a Height of 5 Miles

period gives time for the movements of the atmosphere to equalize in part the differences between ocean and continent and between the upper and the lower air.

Fig. 98 gives a plot of the annual period at the height of 5 miles (8 km.) above St. Louis,[1] a midcontinental station, and also above Europe as determined by Gold.[2] The values for Europe were obtained from sounding balloons launched from seven different observatories. The values as given here are smoothed by means of three.

FIG. 99



Yearly Period of Temperature at a Height of 10 Miles

Fig. 99 shows the yearly periods at the same places at a height of ten miles (16 km.) above the surface. At heights of 5 and 10 miles (8 and 16 km.) above St. Louis, the annual range is less than at the earth's surface, but is still large. The difference between the mean temperatures of January and July at St. Louis is about 48° F., near the earth's surface. At 5 miles it is 33.5° F., and at 10 miles about 28.5° F. Over Europe the annual range is almost as great at 5 miles as at the surface, but decreases at higher levels almost at the same rate as at St. Louis. By harmonic analysis Gold[3] found the annual ranges at 1, at 8,

[1] Blue Hill Meteor. Observatory—Exploration of the Air with Ballons-sondes and Kites, *Annals of the Astronomical Observatory of Harvard College*, Vol. 47, Part I, Cambridge, Mass., 1909.

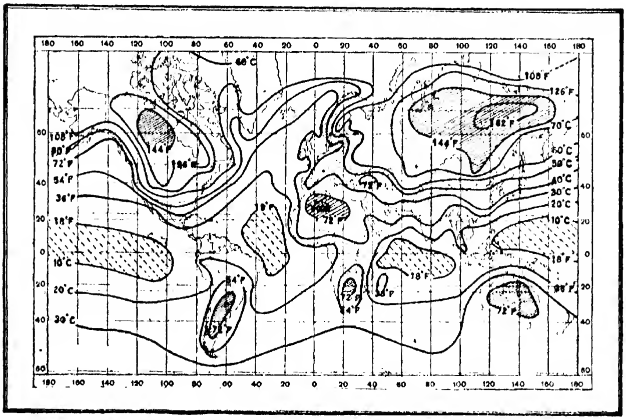
[2] Gold, E.—"The International Kite and Balloon Ascents," *Geophysical Memoirs, No. 5, Meteorological Office*, London, 1913.

[3] *Ibid.*

and at 15 kilometers (0.6, 5 and 9 mi.) to be 26.2°, 26.2° and 13.7° F., respectively, as determined from the means of six stations.

In the middle of the North Atlantic at about 50° N. latitude the annual range is about 18° F. (10° C.) at the surface. The yearly period in the temperature increases from equator to pole. At the equator, there are two maxima and two minima. The maxima tend to occur in April and October, soon after the sun crosses the equator, and the minima after the sun reaches its

FIG. 100



Annual Ranges of Temperature

highest point north or south. The time of occurrence is modified somewhat by the rainy season and on that account the maxima occur at some places as late as May and November. The ranges are greater over equatorial Africa and equatorial America and smallest over the ocean. Over continental Africa the difference between the coldest and warmest month is as much as 12.5° F., while over the ocean it is only about 1°. From latitude 20° to the pole there is in the northern hemisphere a minimum in January and a maximum in July, while in the southern hemisphere, the maximum is in January and the minimum in July. Taking the mean yearly difference between January and July for each ten degrees of latitude north and south of the equator, the following figures are obtained:

TABLE III

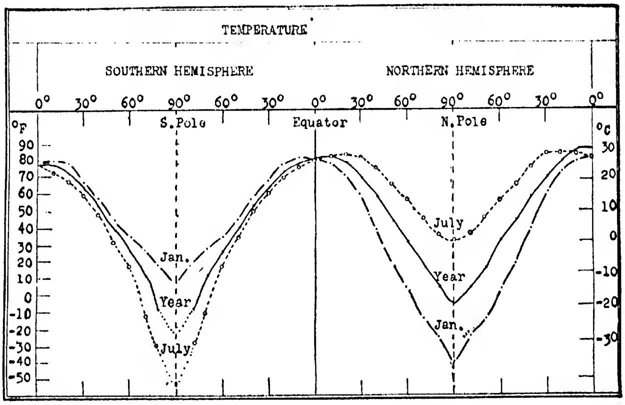
MEAN ANNUAL RANGES OF TEMPERATURE AT DIFFERENT LATITUDES

Latitude	10°	20°	40°	60°	80°
North	4°	12°	35°	56°	60° F.
South	4°	10°	11°	15°	55° F.

It is seen that the annual ranges increase in both hemispheres from latitude 10° to 80°, but more in the northern hemisphere on account of the greater land surface.

The annual range for a large part of the globe appears in Fig. 100, in which are drawn lines of equal annual range for each

FIG. 101



Mean Temperature from Equator across Both Poles

10° C (18° F.). These are derived from observations near the earth's surface. In both hemispheres the maximum ranges occur at the poles and over the polar sides of the continent, while the smallest ranges are over the ocean. The greatest absolute range for the whole earth is over Siberia, about 67° N. and 103° E. The close agreement of the annual ranges at great heights above St. Louis and Europe, as shown in Figs. 98 and 99, leads to the belief that the effects of the land and water largely disappear at an elevation above the surface and the lines of equal range form circles around the polar region where the range is greatest.

Fig. 101 gives a plot of the temperature for January, for July and for the year across the poles of each hemisphere derived from the mean temperatures along each ten degrees of latitude.

The data for the latitudes 60° N. to 60° S., were taken from the chart of annual temperatures in the *Report of the Challenger Expedition.* From 70° N. to the north pole the means were derived from the charts of Mohn given in *The Norwegian North Polar Expedition 1893–1896,* Vol. VI, London, 1905. For high southern latitudes, they were computed by R. C. Mossman from the observations at Cape Adare and on the *Belgica* for the mean latitude of 71°. For the latitude of 78° the mean temperature was derived from observations at three stations, Framheim, Cape Evans and Barrier, as given by Simpson.[4] The monthly means derived from these three stations are:

TABLE IV

MONTHLY MEAN TEMPERATURES AT 78° SOUTH LATITUDE

Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
18.4° F.	7.0°	—5.9°	—18.8°	—25.1°	—25.6°	—28.8°	—32.4°	—24.7°	8.7°	—8.9°	22.3°

It is seen that the temperature is highest in December and lowest in August. Possibly this may be due to the short period of observations, slightly less than one year at Framheim and the Barrier and four years at Cape Evans; but it is not improbable that this is the normal course of the temperature for that part of the world where the day and the year more or less coincide, so that the yearly curve partakes of the unsymmetrical nature of the daily curve, decreasing to a minimum shortly before sunrise and rising to a maximum shortly after noon, which in this case is the summer solstice of the southern hemisphere. No observations are available from the south pole for July, but the observations of Amundsen and Scott give the temperatures for one summer (December and January) near the south pole.[5] The monthly mean for January (7.4° reduced to sea level) was used in computing the curve across the pole for the month.

December was somewhat warmer than January, the monthly mean being 17.3° F., reduced to sea level. The temperature over the Antarctic plateau rarely rises to zero F., and during most of January (midsummer) was about 20° below.

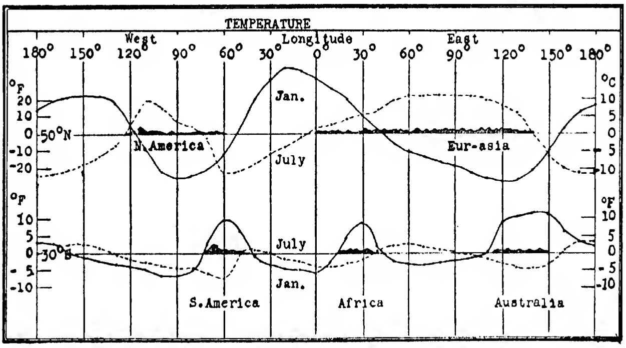
For July and for the year the curves plotted in Fig. 4 were extrapolated to the pole. A curve drawn through the mean temperature for 60° latitude and those for 71° and 78° indicate that the temperature at the south pole, if the pole were at sea level, would be about 50° F. below zero in July; but as the pole is on

[4] Simpson, G. C.—*British Antarctic Expedition, 1910–1913,* "Meteorology," Vol. I, pp. 182-183, Calcutta, 1919.
[5] *Ibid.*

a plateau nearly nine thousand feet above the sea, the actual temperature may be quite different. All the year the temperatures are lower around the south pole than at the same latitudes in the northern hemisphere, so that the yearly means are lower.

At the same latitudes, however, the temperature is not everywhere the same. A plot of the differences from the mean of the latitude is given in Fig. 102 for 50° N. and 30° S. These lines pass nearly centrally over the continental masses north and south of the equator and show greater contrasts than those for other

FIG. 102



Mean Temperature along Latitudes 50° N and 30° S

latitudes north and south. The departures from the mean of the latitude are plotted for each ten degrees of longitude around the world at each of the latitudes given. This plot brings out clearly the contrast between ocean and continent in summer and winter. In summer, the land masses are warm and the ocean relatively cool; in winter, the land masses are cold and the ocean relatively warm. In the northern hemisphere there are two wide continental masses, while in the southern hemisphere there are three of much smaller dimensions east and west. The difference is shown by the difference in the character of the plots in the two hemispheres. The positions of the maxima in summer are not exactly the same as the minima in winter; the difference results from the effect of ocean currents and prevailing winds.

There are, hence, two distinct causes for temperature contrasts: one is the difference between equator and pole, and the other the difference between ocean and continent. Both show a

distinct annual period as the sun moves north and south, and each in its own way sets up a series of annual and semiannual changes which involve the whole of the different elements that make up the weather. These land and ocean masses, polar areas and equatorial zones are the true centers of action of the atmosphere.

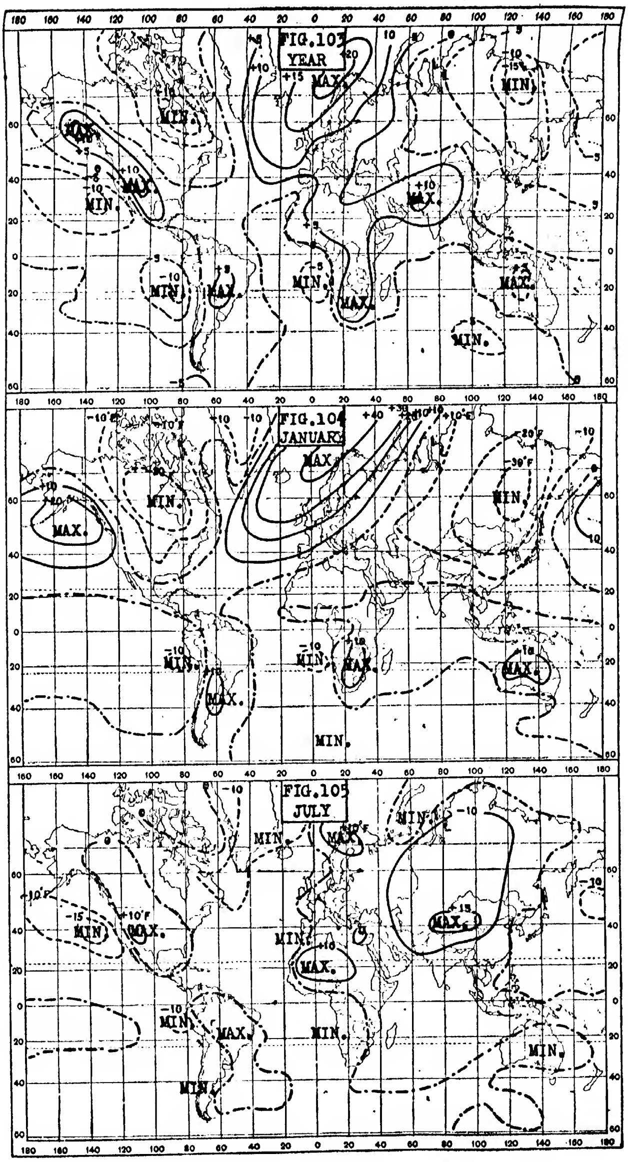
Maps of the departures of temperature from the mean of the latitude are shown in Figs. 103, 104 and 105 for the year and for January and July. In the mean for the year it is seen that between the equator and 30° the land is warmer than the water, while north and south of 40° the land is colder than the water. Near the equator insolation exceeds radiation, while above 49° latitude radiation exceeds insolation.[6] At about 22° N. the greatest heat is found over southern Asia and in Mexico, while at the Arctic Circle, 67° N., the greatest cold is found over Siberia and America at about 130° E. and 90° W. There is also a smaller center of cold over Greenland. The greatest warmth is found in the north Atlantic and north Pacific. In the southern hemisphere at 22° S. the greatest cold is found over the oceans and the greatest warmth is found over the three continents, but as there are no continents at 67° S., no great contrasts occur along the lines of latitudes.

In January, the centers of cold over the northern continents and the contrasted warmth over the oceans are greatly accentuated, as shown by Fig. 104, while the warmth over the continents and contrasted cold over the ocean are accentuated in the southern hemisphere.

In July, Fig. 105, conditions are reversed, except that the greatest heat over the northern continents is found at lower latitudes than the centers of cold in January. The greatest cold is found over the oceans. There are two centers over each ocean, one in the western Atlantic and one in the western Pacific at 50° to 60° N., while near 30° N. there is a center over the eastern part of each ocean. In the southern hemisphere the coldest centers are found over the land, but the eastern sides of all the oceans remain permanently cool and the western sides permanently warm owing to the trend of the ocean currents and of the prevailing winds which cause them.

Because of the various contrasts of temperature described above, there result many centers of heat and cold. The chief centers of cold may be described as follows: (1) the Siberian

[6] Hann, J., *Lehrbuch der Meteorologie*, p. 153, Leipsig, 1915.



Departures of Temperature from the Mean of the Latitude

center, (2) the Hudson Bay center, (3) the Greenland center, (4) the Davis Strait center, (5) the Kamchatka center, (6) the Nova Zembla center, (7) the Hawaii-Californian center, (8) the tropical north Atlantic center, (9) the tropical south Atlantic center, (10) the Easter Island center, (11) the Patagonian center, (12) the Indian Ocean center, (13) the Australian center, and (14) the Antarctic continental center. Some of these, like the Greenland center, the tropical ocean centers and the Antarctic continental center, are permanent centers of cold, while the others alternate with the season between continent and ocean, the colder air being over the continent in winter and over the adjacent ocean in summer. Greenland and the Antarctic continent are not heated in summer because these are permanent snow and ice areas. Snow reflects rather than absorbs a large part of the solar radiation and is also a good surface radiator.

The centers of warmth may be called: (1) the Iceland-Norway center, (2) the Aleutian Islands center, (3) the Arizona center, (4) the Sahara center, (5) the Mediterranean center, (6) the Persian center, (7) the East Indian Islands center, (8) the West Indian Islands center or northern Brazil center, (9) the Australian center, (10) the South African center, (11) the northern Argentine center, (12) the McMurdo Sound center, and (13) the Weddel Sea center.

Some of these, like the Iceland-Norway center, the East Indian and the West Indian centers and the Antarctic centers, are permanent areas of warmth, while the others shift or change sign with the season.

In addition to changes with the season, the intensity of these areas varies with changes in solar radiation and these changes markedly influence the weather, as will be seen later.

The average annual distribution of temperature over the globe is shown in Fig. 106.

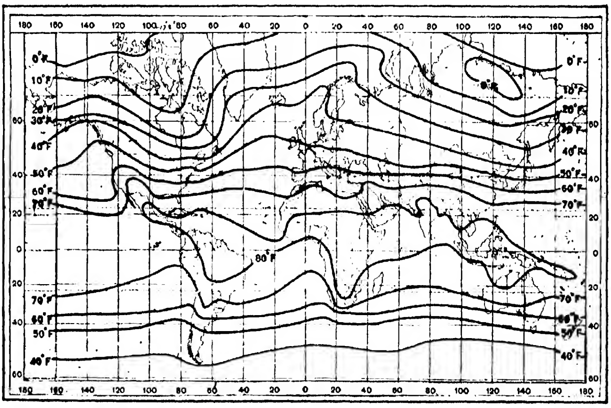
THE YEARLY PERIOD IN PRESSURE

The general form that the atmosphere would take on a revolving earth unaffected by differences of temperature would be elliptical, bulging out at the equator and depressed at the poles. The form actually assumed under the influence of temperature and air motion as determined from the observed atmosphere pressure at each ten degrees of latitude is a more complicated form, in which the highest pressure, indicating the largest air mass, is

found at 30° N. and 30° S., while less marked maxima are found at the poles, and minima are found at the equator and at 60° N. and 60° S.

The change in the form of the pressure curve with different epochs of the year is illustrated in Fig. 107, in which are given plots of the mean pressure for each ten degrees of latitude between equator and pole in both hemispheres for different months. The upper curves in the plot give the pressure distribution for January and July, the warmest and coldest months of the year

FIG. 106



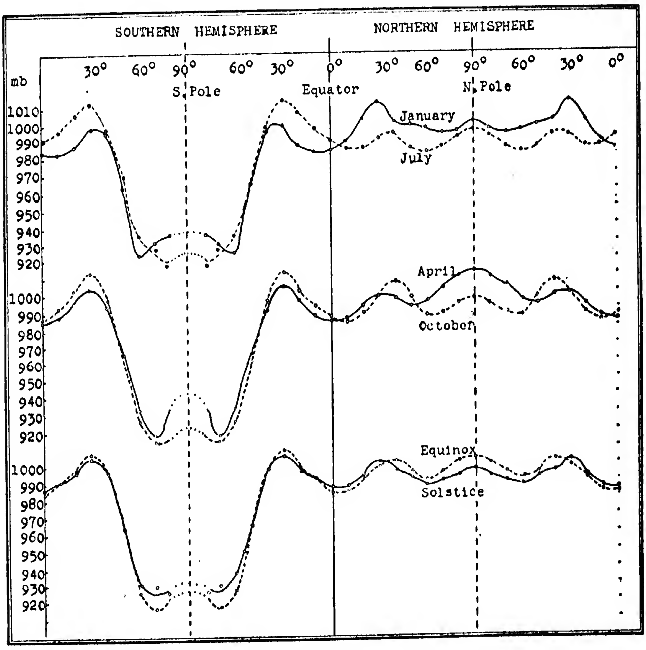
Annual Average Isotherms

in the two hemispheres, January being the coldest month in the north and the warmest in the south and July the reverse. The plot for these months brings out three facts very clearly: (1) The contrast of pressure in each hemisphere between thirty degrees of latitude and the polar region is more marked in the coldest month of each hemisphere when the contrast of temperature between the poles and equator is greatest (see Fig. 101) and the wind movement is greater (see Figs. 114 to 120); in other words, the increase of temperature contrast and the deepening of the polar cyclones are coincident. (2) The low pressure near the equator swings back and forth with the sun, being always on that side of the equator where the sun's rays are most nearly vertical to the earth's surface. (3) The pressure averages lowest in that hemisphere, which is the warmer. In the northern hemisphere the

pressure is lower in July in every latitude between 5° and 90°; while in January it is lower in every latitude between 0° and 60° in the southern hemisphere. This means that a large mass of air must pass from the northern to the southern hemisphere and back again each year.

The curves in Fig. 107 for April and October show that the pressure contrasts between latitude 30° and the pole are most

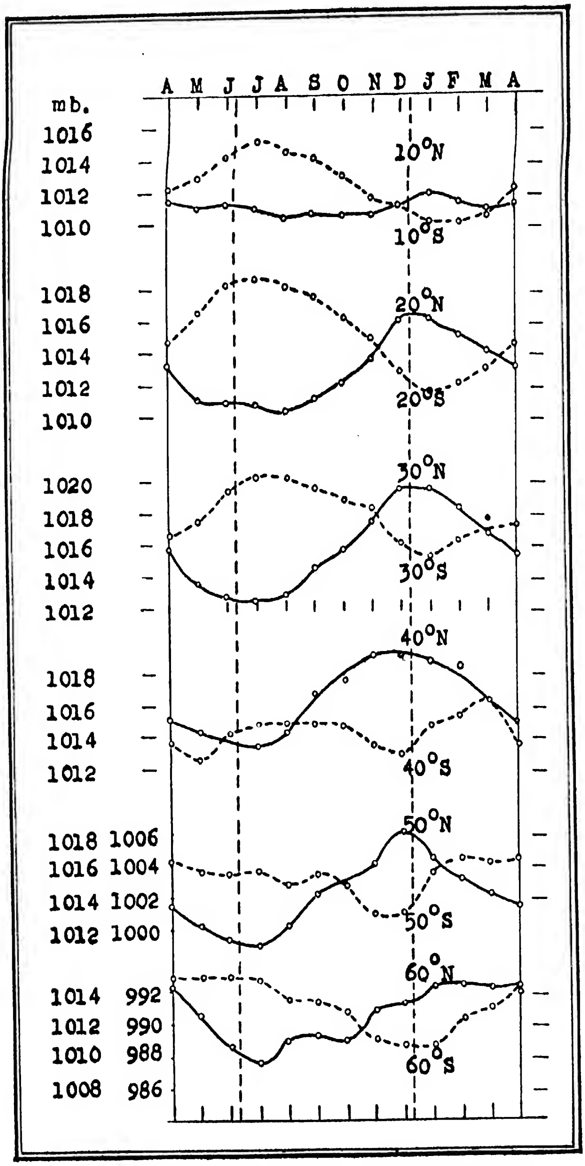
FIG. 107



Mean Pressure for Each 10° of Latitude from the Equator Across Both Poles

marked in October in both hemispheres, while in April there is a maximum of pressure at the north pole and also at 78° S., the nearest station to the south pole. By taking the mean of the pressures for January and July and of those for October and April, separate means are obtained for the solstices and equinoxes. These are plotted in the lower set of curves in Fig. 107. It is seen that the pressure contrasts in the southern hemisphere are

Fig. 108

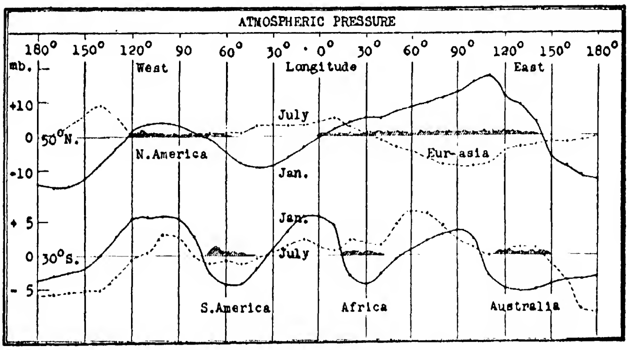


Yearly Period of Pressure for Different Latitudes and Months

greatest at the time of the equinoxes. The pressure is then lowest around the south pole and at the equator, while it is higher than the mean at 30° S. and 35° N. and also around the north pole. These changes imply a semiannual period in the pressure as well as an annual period.

Fig. 108 gives a series of plots of the mean pressure for each ten degrees of latitude month by month, beginning with April, showing the annual period between latitudes 10° and 60° N. and S. The means for the northern latitudes are in continuous lines and those for southern latitudes in broken lines. The two sets of

FIG. 109



Plot of Mean Pressure along Latitudes 50° N and 30° S

curves follow opposite courses, the pressure being low in summer and high in winter in each hemisphere, the greatest annual ranges being found at latitudes 20° to 30°. Since the pressure cannot fall without a change in the mass of the atmosphere within the region where the fall occurs, this change of pressure implies the movement of an immense mass of air from one hemisphere to the other in the opposite direction to the movement of the sun. Between latitudes of 10° and 60° the mean annual change is about 0.5 per cent of the total atmospheric pressure. This is roughly equivalent to 13,321,000,000,000 tons of air transported a distance of 2000 miles, a quantity so vast that all the ships and all the railways in the world, though multiplied many thousands of times, could not transport it.

Besides the movement of air between the hemispheres north and south of the equator there is also a vast movement of air from

continent to ocean when the continents are heated by the summer sun, and back again when the continents are chilled by the winter's cold.

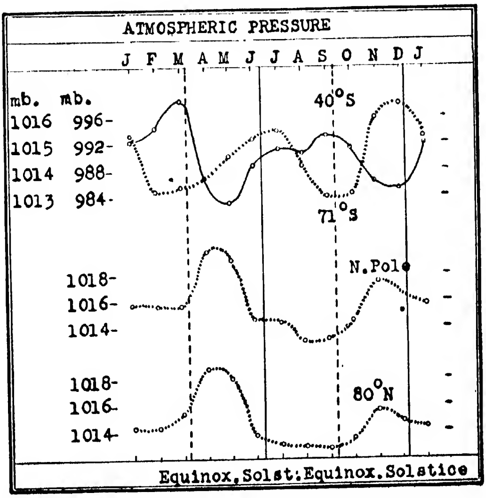
The low pressure over the continents in summer and the high pressure over the ocean is well shown by the curves in Fig. 109, showing the mean pressure at every ten degrees of longitude along the 50th degree of latitude north and of 30 degrees south. July is midsummer in the northern hemisphere and January midsummer in the southern. The curve for January, midwinter in the northern hemisphere, shows a pressure distribution nearly the reverse of that in summer, but in the southern hemisphere the distribution is only partly reverse, owing to the persistent low temperatures of the oceans, especially on their eastern sides. In this plot (Fig. 109) the positions of the continents are indicated by the irregular contours at the base of the diagram, and the position of the ocean by a straight line. The curves for the parallels of 30°, 40° or 60° show similar changes, but the range along the parallels of latitude decreases toward the equator and also decreases in high northern latitudes. Charts of the departures of pressure from the mean of the latitudes are shown in Figs. 111, 112, 113. These were made in the same way as the temperature anomalies in Figs. 103, 104, 105, and the data were derived from the same sources. As explained previously, the distribution of air pressure results from two distinct causes: first, from differences in the density of the air, due chiefly to temperature difference, and second, from air movement on a rotating earth, as a result of which, air moving toward a central area, whether warm or cold, is thrown into a circulation, which tends to lower the pressure within the central area. If air is moving inward toward a warm area, the inward motion is likely to be at a low level near the earth's surface; while motion into a cold area is likely to take place aloft where there is less friction, and consequently more rapid air circulation and a greater reduction of pressure. This reduction more than offsets the tendency to increased pressure due to the greater density of the cold air, unless large irregularities in the earth's surface interfere with air movement. Air moving from the equator to the pole is moving toward a central area under conditions especially favorable for cyclonic development. Whatever view may be held as to the origin of the west-to-east circulation of the atmosphere on the polar side of 40° latitude, meteorologists are agreed that an increase of wind velocity should accompany an increased gradient and a decreased velocity a decreased gradient. Thus, an increased wind circula-

tion in winter accompanies the increased gradient resulting from the greater difference in pressure between 40° latitude and the Arctic and Antarctic circles, shown in Fig. 107, and this increased air circulation clearly results from increased temperature contrast between equator and pole.

THE HALF-YEARLY PERIOD IN PRESSURE

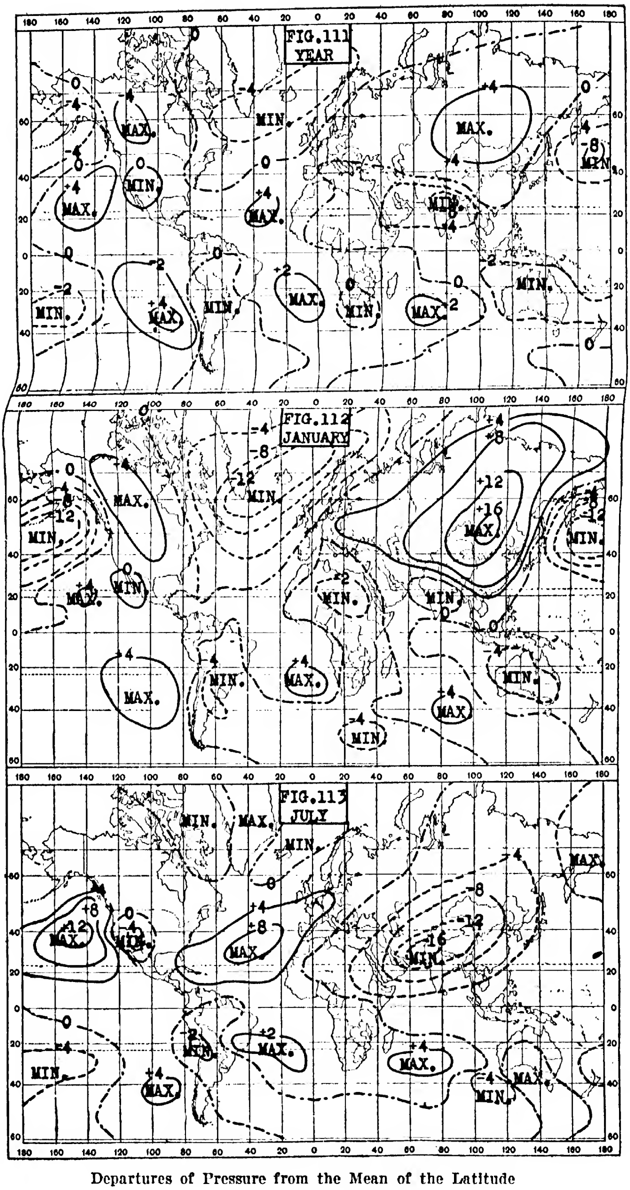
The increased intensity of the polar cyclone at the equinoxes is evident from Fig. 107, in which the pressure is higher in April and October at the 30th parallel of latitude and lower in the polar regions, as a result of which there is a semiannual oscillation of

FIG. 110



Opposing Semi-annual Oscillations of Pressure at 40° S Latitude and at High Southern and Northern Latitudes

pressure in opposite directions in the temperate and polar regions. In high latitudes this period becomes even larger than the annual period. This semiannual oscillation is well seen in the plots of monthly mean pressure for 40° S. and 70° S., as shown in Fig. 110, in which the continuous curve is drawn from the monthly pressures at 40° S. and the broken curve from those at 70° S. The double maxima of pressure also occur in high northern latitudes, as seen by the lower curves in Fig. 110, showing the mean



Departures of Pressure from the Mean of the Latitude

monthly pressures at 80° N., and at the pole. This semiannual period is not visible at lower latitudes in the northern hemisphere, except when the annual period is eliminated.

If the components of the annual and semiannual periods are computed from the monthly means of pressure at each latitude by means of harmonic analysis, the results shown in Table V are obtained.

TABLE V

TIMES OF MAXIMA OF PRESSURE AND ANNUAL RANGES IN MILLIBARS IN DIFFERENT LATITUDES, COMPUTED BY HARMONIC ANALYSIS OF 12 MONTHLY MEANS OF PRESSURE

	YEARLY PERIOD				HALF-YEAR PERIOD			
	Maxima Occur		*Ranges*		*Maxima Occur*		*Ranges*	
	North	*South*	*North*	*South*	*North*	*South*	*North*	*South*
Pole	Mar. 21	....	3.92	......	May 10	....	7.36	......
80°	" 29	Feb. 11	3.58	8.28	" 4	June 6	7.20	4.94
70°	" 7	Dec. 8	3.76	2.70	Apr. 28	" 9	3.12	2.18
60°	Feb. 10	May 31	4.52	5.02	Mar. 29	July 6	1.94	2.02
50°	Dec. 24	" 8	5.64	2.18	May 6	Mar. 3	1.51	3.36
40°	" 19	....	6.00	0.48	" 14	Feb. 10	0.24	4.46
30°	Jan. 7	Aug. 10	7.10	4.44	Jan. 7	Mar. 9	1.06	1.82
20°	" 19	July 29	5.54	6.54	" 2	May 11	1.86	0.70
10°	Feb. 28	" 31	1.02	5.94	" 3	" 20	0.94	0.38
Equator	....	" 21	......	2.56	" 31	....	......	0.55

The ranges given in the table are twice the values of the amplitudes. The table brings out the fact that the annual interchange of air across the equator is chiefly in the region between the equator and 60° latitude. In the yearly period, the maximum pressure in these latitudes occurs in the winter of each hemisphere. In the northern hemisphere the maxima in the different latitudes occur between December 24 and February 28, while in the southern hemisphere they occur between May 8 and August 10. The maximum yearly range in this region is at 30° N. and 20° S. Near the north pole, 70° to 90°, the maximum occurs in March and near the south pole, 65° to 78°, it occurs in summer, but in these high latitudes the half-yearly period has a larger amplitude than the yearly period. In the half-yearly period the maxima occur in spring and autumn near the poles and occur in winter and summer in 30° to 40° latitudes.

The increased pressure differences at the time of the equinoxes are also shown by the pressure difference between south Georgia and the Orcadas (South Orkneys) given in Table VI which are

clearly associated with increased atmospheric circulation in the polar cyclones at these epochs. Wind observations in midocean away from the land are not numerous, but the observations in the Orcadas in mid-Atlantic show clearly this double maximum in wind velocity, as is seen from the means in miles per hour in Table VI.

TABLE VI *

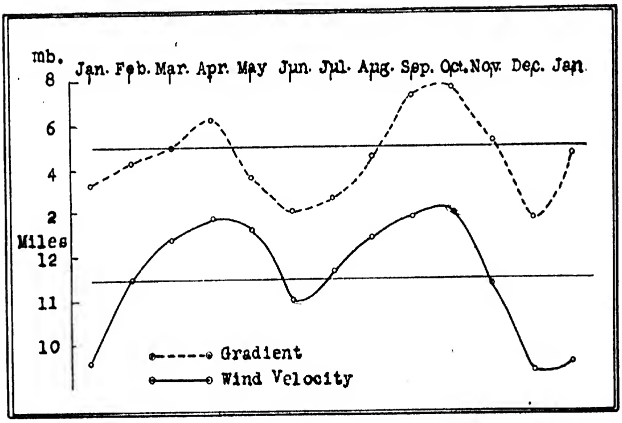
PRESSURE GRADIENT AND WIND VELOCITY IN THE SOUTH ATLANTIC

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Gradient (mb)..	3.3	4.3	4.9	6.2	3.7	2.0†	2.8	4.5	7.2	7.6	5.1	1.6†
Wind velocity...	9.6	11.5	12.4	12.8	12.6	11.0†	11.7	12.4	13.0	13.0	11.4	9.4†

* From data compiled by R. C. Mossman. † Minima.

These variations in the pressure gradient and in the wind velocities, plotted in Fig. 114, follow closely the variations in intensity of the southern polar cyclone indicated by the greater pressure

FIG. 114



Pressure Gradient between South Georgia and South Orkney Islands and Wind Velocity in the South Orkneys

contrasts. The lower pressure at the equinoxes is probably caused by an increased atmospherical circulation resulting from a decreased convectional interchange between continent and ocean at the equinoxes when the temperature of land and ocean approach equality. Thus the equator-pole and continent-ocean circulation are to some extent complementary and alternate in intensity.

This alternation offers a satisfactory explanation of the semi-annual variation in the pressure illustrated in Figs. 110 and 114.

YEARLY AND HALF-YEARLY PERIODS IN WIND VELOCITY

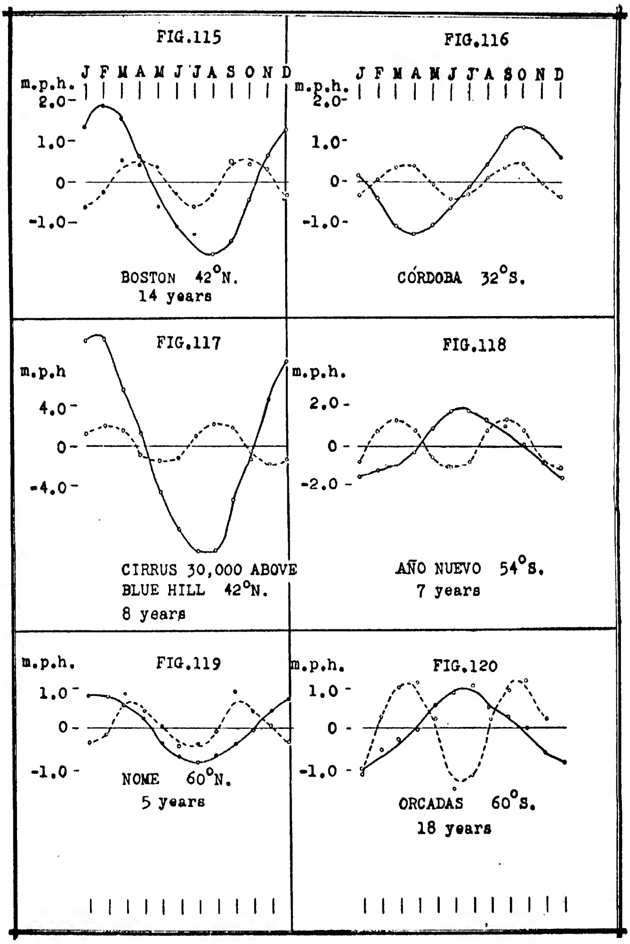
The two maxima of wind velocity, the one in spring and the other in autumn, observed in the Orcadas, are found also in the northern hemisphere, as is seen from the following mean velocities in miles per hour for the years 1871–1884 at Boston, on the Atlantic coast, 42° N., 71° W.:—

TABLE VII

OBSERVED AND ANALYZED WIND VELOCITIES AT BOSTON

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Observed Velocities	9.9	10.6	**11.3**	10.1	8.8	7.8	7.4	7.1	8.2	9.0	**10.3**	10.0
Semiannual Period	− 0.6	− 0.4	+ 0.5	+ 0.4	+ 0.3	− 0.3	− 0.6	− 0.3	+ 0.5	+ 0.4	+ 0.3	− 0.3
Annual Period.	+ 1.3	+ 1.8	+ 1.6	+ 0.5	− 0.7	− 1.1	− 1.3	− 1.8	− 1.5	− 0.6	+ 0.7	+ 1.1

Departures from the mean of the year were analyzed numerically into a half-yearly and a yearly period. The results are given under the observed velocities. Adding the sum of these two periods for each month to the mean velocity (9.2) gives the observed velocity. The results would give a more regular curve if analyzed harmonically, but the numerical process is sufficient to show that the principal periods are yearly and half-yearly and that the amplitude of the half-yearly period is between a third and a quarter of the amplitude of the yearly period at Boston; while at the Orcadas in midocean, 60° S., the amplitudes of the yearly period and half-yearly period are nearly equal. In Figs. 115 to 120 are given plots of the yearly and half-yearly periods for various stations in the northern and southern hemisphere. Fig. 115 shows the two periods for the wind at Boston. Fig. 116 shows the yearly and half-yearly period for Cordoba, a midcontinental station, 31° 25′ S., 64° 12′ W. Fig. 117 shows the yearly and half-yearly movement of the cirrus at a height of 30,000 feet (9000 m.) above Blue Hill, ten miles south of Boston. Fig. 118 is for Año Nuevo, a coast station 54° 39′ S., 64° 10′ W. Fig. 119 is for Nome, a coast station in Alaska, 64° 30′ N., 165° 24′ W. Fig. 120 is for the Orcadas in the South Atlantic, 60° S. Excepting Cordoba, the stations show the maximum of the yearly period near midwinter and the minimum near midsummer; but, as the seasons are reversed in the two hemispheres, the yearly curves are reversed. At Cordoba the yearly maximum is delayed, owing to another factor which influences the surface wind veloci-



Annual and Semi-annual Periods in Wind Velocity

ties over large land areas, and that is the vertical convection currents of the afternoon which cause a mixing of the surface and upper winds with an increased velocity at the surface and a decreased velocity at a higher level (3000 to 6000 ft.). This effect is at a maximum in the spring (March to May in the

northern hemisphere, and September to November in the southern).

The maxima for the half-yearly period occur near the equinoxes in both hemispheres and are apparently the same at all levels, as indicated by the cirrus movements at Blue Hill, Fig. 117. At the stations in temperate latitudes the half-yearly period has an amplitude varying between one third and one fifth of the yearly period, while in extreme latitudes above 60° the half-yearly appears to be as large as the yearly period.

An investigation of the two periods at a number of other stations indicates that at the majority of stations the periods follow the same course as those given here; but there were a few stations in which the curves are different, apparently as the result of local influences. Tropical stations, like Batavia and St. Helena, show the semiannual period with the same phase as do stations outside the tropics. The annual period, as explained previously, is probably caused by the increased temperature contrast between the equator and the pole in winter; while the semiannual period is assumed to be due to an increase in the circumpolar circulation when it is least interrupted by the exchange of air between ocean and continent. As a result of this increased velocity the air is carried out from the polar regions near the equinoxes and piled up at the 40th latitude, as shown when discussing the annual periods in the pressure (see Fig. 107).

THE YEARLY PERIOD IN THE RAINFALL

As rainfall is caused by ascending currents of moist air, there are a great many factors determining its yearly variations, as a result of which, stations near each other may have very different annual periods.

Mountains in the path of the prevailing winds cause the winds to ascend and the rainfall reaches a maximum when the winds are strongest. Good examples are found in southern Chile and near the northern Pacific coast of the United States, where winds from the Pacific are lifted by mountains. These rains are heaviest in the winter half-year, when the general circulation is greatest. Rainfall caused in this manner is greatest at a certain height on the mountainside dependent on temperature, dew point, slope of the mountain, wind velocity and direction; above that height the rainfall diminishes, because the quantity of water vapor in the air diminishes.

Winds moving toward each other from nearly opposite direc-

tions ascend at the place of meeting and thus produce rain. Near the equator, where the winds are nearly of equal temperature, the rainfall forms a belt overspreading each side of the meeting place; but where one current is the colder, as happens in high latitudes, the ascent takes place chiefly in the warmer wind.

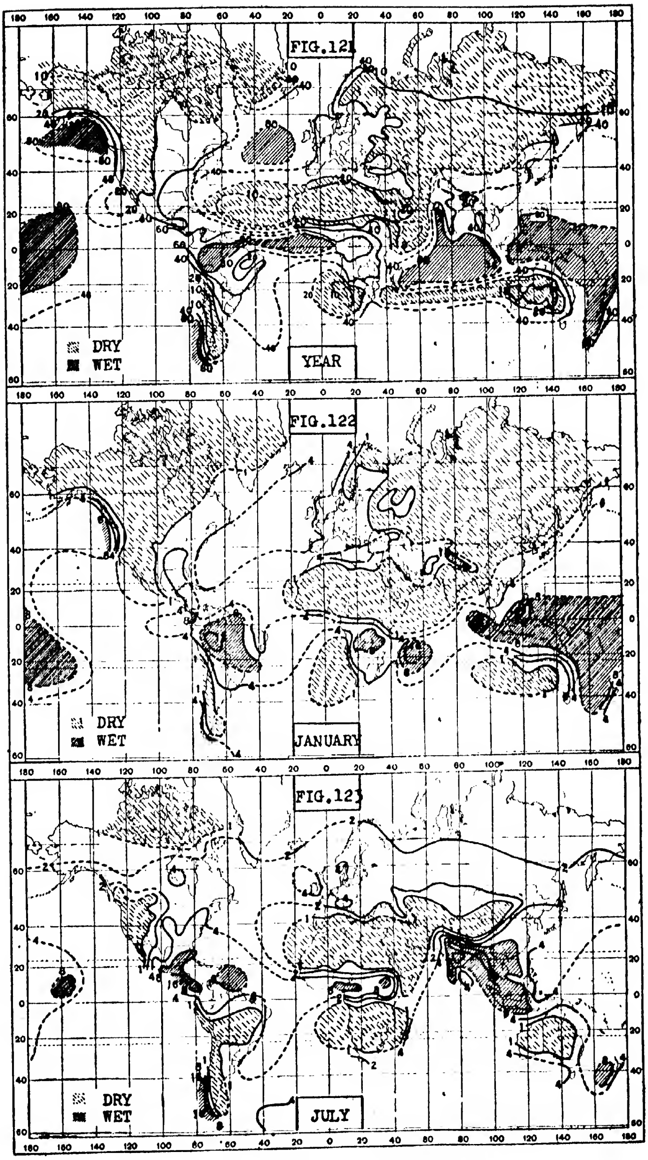
The meeting place of the equatorial winds is near the belt of highest temperature, which follows the sun back and forth across the equator, so that, for places very near the equator, there are two maxima and minima each year.

Winds converging toward a central area must also ascend in part, because the area occupied by the mass of air is steadily diminishing. Hence, regions having a more or less permanent area of low pressure, as the North Atlantic and the Indian Ocean, are regions of frequent rainfall, and the rainfall tends to be greatest at the time of year when the pressure is lowest. Continental areas, over which the pressure is lowest in summer, usually have the greatest rainfall in summer.

The frequency of passage of revolving storms also influences the quantity of rainfall and affects the annual period. Another factor which determines the annual period is the quantity of moisture in the air. The amount is usually greatest when the temperature is highest, except when a place is near a body of warm water, in which case the supply of moisture is greatest when the temperature of the water is highest. In that case the amount of water in the air may lag behind the maximum air temperature. On the south Atlantic coast of the United States and on the coast of northern Argentina the water temperature is highest in autumn, so that the heaviest rainfalls in those regions are in autumn. The highest water temperature and the heaviest rainfall also occur in northeastern Europe in the autumn. On the other hand, when a cold current of water flows near a coast there is likely to be a minimum of rain at the time when the water is coldest.

On the New England coast there are three maxima of rainfall, one in winter, probably caused by the greater frequency of storms, a second in July to August, probably due to the greater heat of the summer, and a third in early autumn at the time when the water is warm along the coast and tropical cyclones are most frequent.

The distribution of rain over the land surfaces of the globe for the year and for July and January are shown in Figs. 121 to 123. The great similarity of the rainfall at the same latitudes north and south of the equator in the Americas is shown in Fig. 124, in which the south pole is placed upward to correspond in position



Normal Distribution of Rainfall

to the north pole, while east and west remain the same. It can be seen that the heavy rainfall of the north Pacific coast of the United States and Canada corresponds to the heavy rainfall of southern Chile, while the arid region of Lower California corresponds to the arid region of northern Chile.

The heavy rainfall of Florida and the West Indies corresponds to the heavy rainfall of eastern and southern Brazil and northeastern Argentina. Moreover, the annual changes are alike for the same latitudes and the same relative positions. The rainfalls in southern Chile and on the north Pacific coast between Oregon and Alaska have maxima in winter. This winter maximum also extends into western Chubut and Rio Negro. Over the interior of the continents, the maxima are in summer. This rule applies to the Mississippi valley of the United States and to central and western Argentina.

On the Atlantic coast of northern Argentina and of the southern United States the maxima of rainfall are in autumn. It must be borne in mind, however, that the seasons are reversed in the two hemispheres. In the southern hemisphere midwinter occurs in July, and in the northern in January.

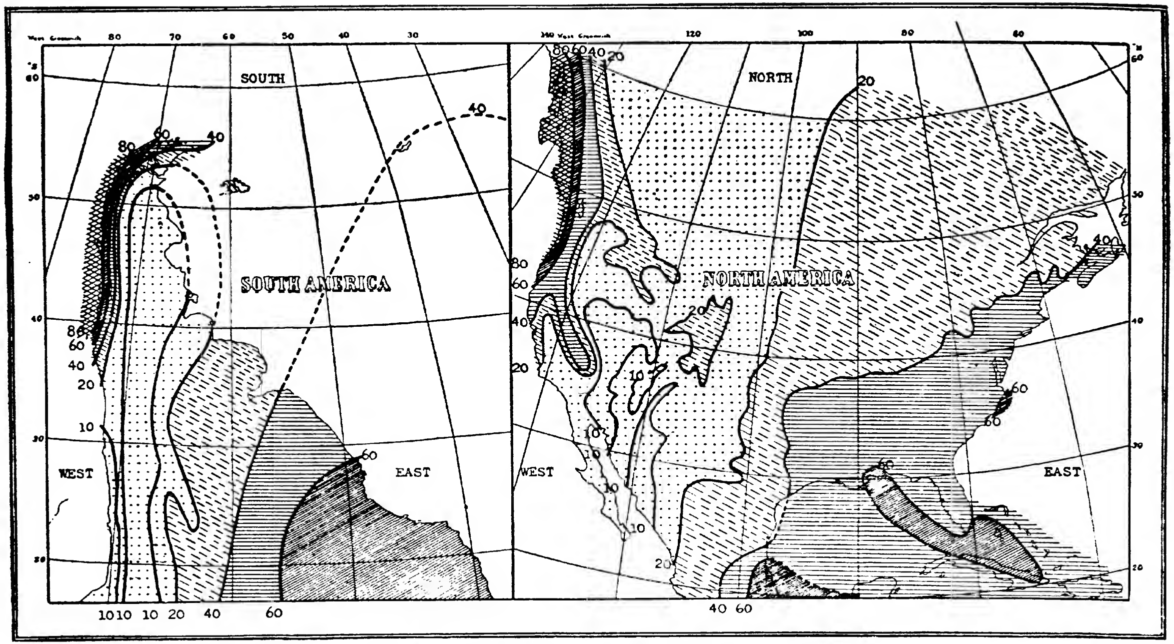
This similarity in distribution and annual change results from the similarity of the wind system and ocean currents in the two hemispheres. When reversed in this way the paths of the traveling centers of high and low pressure in the two hemispheres show a striking similarity.

THE YEARLY PERIOD IN MOISTURE AND CLOUDS

The absolute amount of water vapor in the air depends so greatly on temperature that the annual period in vapor pressure follows closely the annual period of temperature all over the world, except that the times of the maxima and minima usually lag somewhat behind those of temperature. In many cases the lag is as much as a month.

The relative humidity is usually largest in autumn and winter. Radiation of heat from the ground and lower air is the main factor in bringing the surface air to the saturation point. When there is more actual vapor in the air, as there is in late summer and autumn, the saturation point is reached oftener with an equal degree of radiation, so that the autumn usually has higher relative humidity than the spring, although the greatest radiation and, generally, the greatest humidity are in the winter.

FIG. 124



Comparison of the Rainfall of North and South America

The normal distribution of clouds by latitude is shown by the following figures compiled by S. Arrhenius from the cloud charts of Teisserenc de Bort.

TABLE VIII

Latitude	70° N.	60°	50°	40°	30°	20°	10°	equator	10°	20°	30°	40°	50°	60° S.
Cloudiness %	59	61	48	49	42	40*	50	58	57	48	46*	56	66	75

* Minima.

It is seen that the cloudiness is the reverse of that of the pressure shown in Fig. 107, and probably, if data were available for the whole world, would show similar annual changes, the cloudiness increasing as the pressure falls. The factors which determine the annual amount of cloudiness are: (1) the absolute humidity, (2) the relative humidity, (3) the height above sea-level and (4) the frequency of ascending currents, which in turn are dependent on the winds and temperature. No instrument for recording cloudiness has been generally adopted, and estimates of the amount of cloudiness are attended with many difficulties, depending on the kind of cloud observed and its position in the sky. The number of published observations are relatively scarce. For these reasons it is not possible to map out any general laws regarding cloudiness for the world at large.

The following table shows the percentage of sky covered by clouds at several stations in the southern hemisphere as given in "El Clima de Argentina" by W. G. Davis:

TABLE IX

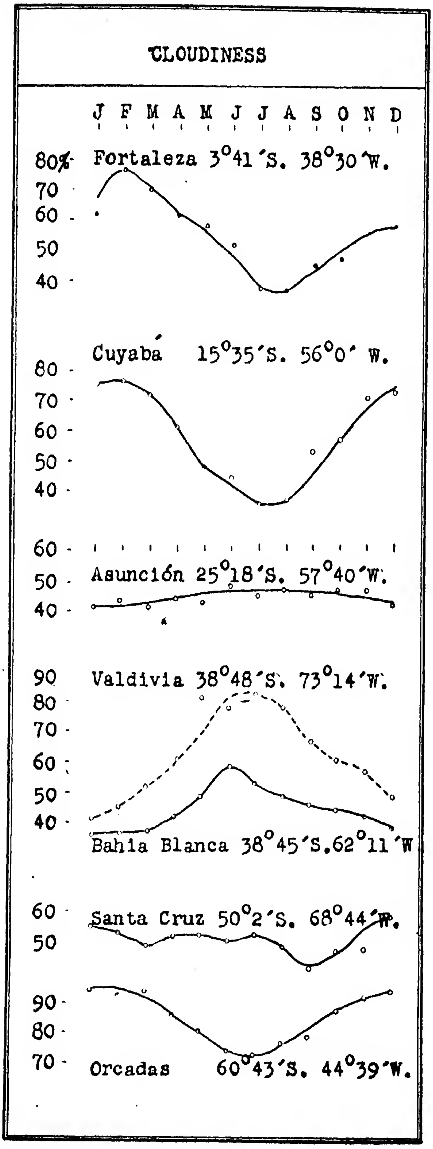
CLOUDINESS IN PER CENT

	Latitude	*Longitude*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Asuncion	25° 18′ S.	57° 40′ W.	41	44	42*	46	43	49	45	47	46	47	43	25
Cordoba	31° 25′ S.	64° 12′ W.	51	52	50*	55	60	64	53	48*	49	51	52	54
Santa Cruz ...	50° 2′ S.	68° 44′ W.	55	53	49*	52	52*	50	51	49	40*	47	47	58
Orcadas	60° 43′ S.	44° 39′ W.	94	92	92	86	80	74	73	76	78	88	91	92

* Minima.

In the Argentine there are in general two maxima of cloudiness, one in June and the other in December, the chief maximum being in June at the northern stations and in December at the southern. At the Orcadas and at stations in the extreme south of Chile and Argentina, there is a single maximum in midsummer. One reason for the minimum in winter in the Orcadas is that in winter these islands are surrounded by ice, so that the climate becomes to some extent continental. In the center of the large continental masses like Asia and North America, the skies are clearest in

FIG. 125



Annual Period of Cloudiness—South America

winter. The explanation does not apply, however, to the south of Chile and Argentina.

From the tabulated percentages of cloudiness in Peru, Brazil, and Chile, published by R. C. Mossman in the *Quarterly Journal of the Royal Meteorological Society,* London, Vol. 46, p. 296, it is apparent that in the tropical part of Brazil in the interior from 0° to 25° S., the maximum of cloudiness is in summer, but in the middle latitudes of Argentina and Chile from 25° to 45° S., the maximum cloudiness is in winter, while in high latitudes south of 45°, the maximum is in summer.

This change with the latitude is represented by a plot of typical stations in Fig. 125.

CHAPTER IV

TEMPERATURE AND THE WEATHER

SUMMARY

The temperature and pressure are found to fluctuate irregularly at places in temperate latitudes, and as these changes progress from place to place, they are shown to have characteristics similar to waves in water, in that there is a combination of fluctuations of many different lengths of oscillation and differences in the rate of progress from place to place, depending on the wave length, that is on the interval between the crests of the waves.

The temperature changes are analyzed into different classes of waves for North America and for South America and their rates of progress from place to place are shown by means of curves and by means of charts. Plots are given of the temperature changes at different heights in Europe and America showing that the temperature changes extend from the earth's surface to great heights and involve a large part of the atmosphere.

The various weather elements, temperature, pressure, winds, rainfall and cloudiness, are so closely related that it is possible to begin the chain of sequences by considering any selected element as the cause of the others.

The chain of causes may be taken in the following order: (1) temperature distribution causes differences of pressure; (2) pressure differences cause winds; (3) winds ascending mountains, or converging to a center or to a line cause clouds and rain. Or one may start with the pressure and say: (1) pressure differences cause winds; (2) winds cause temperature differences. Or else reverse it and say that winds cause pressure difference, etc., or that condensation of moisture into clouds and rain liberates latent heat, which causes pressure differences and the remaining sequences of wind and weather.

The first order of sequences is the one I have accepted as being most in accord with physics and the known facts, starting with the sun as the cause of temperature differences. But, whatever the sequence followed, the elements so react on each other that under certain circumstances any one may be the immediate cause of the other. Thus, although the winds over any region may be primarily due to temperature contrasts over a wide area, as, for

example, the difference between continent and ocean, as soon as air begins to move, it modifies both pressure and temperature. If the general winds blow across a local current of cold water, it is properly considered that the low temperature on the lee shore is caused by winds; so, also, condensation caused by converging winds cools the lower air, while at the same time the upper air is warmed, both of which processes modify the pressure and may cause an increase in the velocities of the inflowing winds. In general winds from the direction of the pole are cold and from the equator warm. Beginning with the temperature, it is proposed to consider as fully as possible the relations of the different elements to each other.

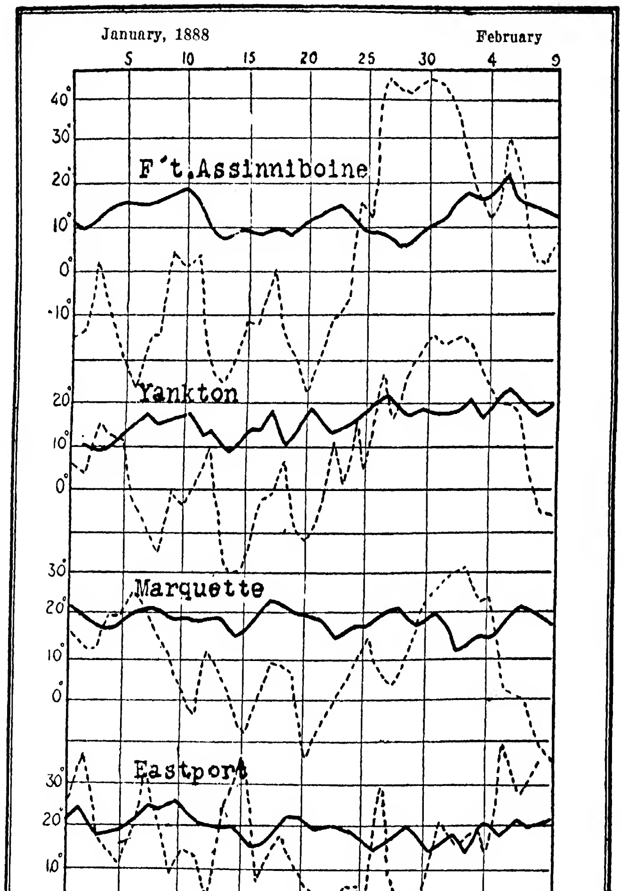
When plots like Figs. 126 and 127 are made of the temperature or pressure, there is seen a complex series of rises and falls which bear a resemblance to the rises and falls of the surface of the ocean. As one stands on the shore when a gentle wind is blowing, he sees small ripples formed on the surface of the water by the wind. These ripples rise and fall with the movements of larger waves coming in from a distance and these larger waves rise and fall on the bosom of large ocean swells, which in turn rise and fall on the surface of the tides, those far slower movements caused by the moon's motions. When the rates of movement of the maxima or minima of atmospheric pressure or of atmospheric temperature are timed from one station to another, there is found an additional analogy to ocean waves in that the waves of different frequency move with different speeds. The longer the interval of time between the crests of the ocean waves at any point the more rapid is the movement of the wave. In discussing the propagation of ocean waves Cornish[1] says:

"When waves are driven outside the wind area and left to themselves to travel over considerable distances, the original complex and irregular waves are analyzed into a series of simple, regular waves of graduated lengths. The longer and swifter are in front, the shorter and slower in the rear; the shorter components flatten out very quickly as they travel, whereas the longer components preserve their height with but little diminution for long distances and reach places far distant from the windward shore, where the water will heave with a long-period undulation."

The wavelike undulations in plotted curves, caused by the progressive movement from place to place of changes of tempera-

[1] *Monthly Weather Review*, Vol. 48, No. 3, p. 127, Washington, March, 1920.

FIG. 126

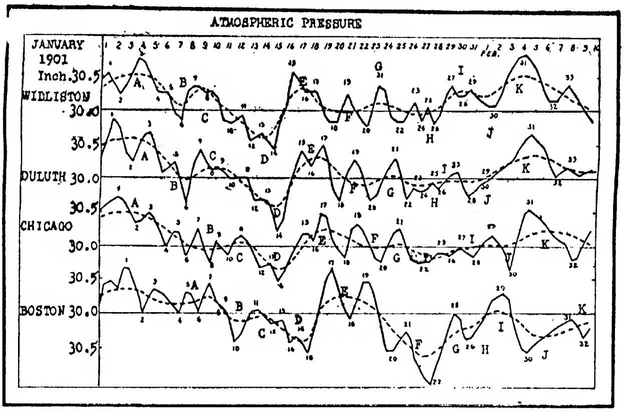


Plot of Temperatures Showing Progress of Temperature Waves Across the United States in January and February, 1888

ture or pressure, are not of the nature of ocean waves, but do resemble them in this feature of complexity and differences of speed of progress, as is seen when curves for different places in the same region are compared; only the long waves move slower rather than faster than the short waves.

When the different classes of temperature waves are well marked and of considerable difference in length, the difference in progressive motion can be seen without analysis, as in Fig. 126, showing a plot of the observed temperatures at various stations in the United States in 1888. The four stations given in the plot are

Fig. 127



Pressure Changes in the United States Showing Wave-like Oscillations

Fort Assiniboine, Montana; Yankton, South Dakota; Marquette, Michigan; and Eastport, Maine. The continuous curves in the plot show the normal temperature for each day, and the broken curves show the observed temperature.

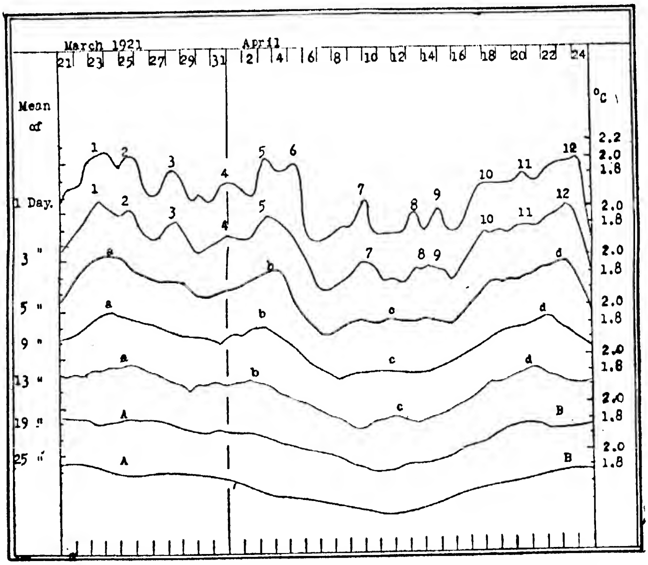
Several different methods have been tried for analyzing meteorological changes into waves of greater and lesser frequency:

(1) A graphical method may be used in which a broken line *A, B, E* is drawn through the shorter undulations, and then another line may be drawn through the waves *A, B, E* (see Fig. 127; see also Fig. 146).

(2) A numerical method may be used in which successive columns of numerical means are derived from the observed values. This latter is done by making a form, or table, in the first column

of which are placed the dates; in the second column are placed the observed values; in the third column are placed the means of each consecutive three of the observed values (1st, 2d and 3d, then 2d, 3d and 4th, etc.); in the fourth column is placed the mean of each four consecutive values; in the fifth column is placed the mean of five, etc. Or the process may be shortened by taking only means of 3, 5, 7, etc. The unit of time used may

FIG. 128

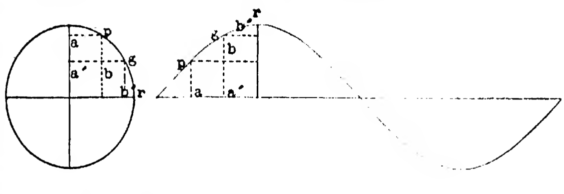


Temperature at Buenos Aires in March to April, 1921, Analyzed Numerically into Waves of Different Lengths

be hours, half-days, days, months or years. This process of smoothing does not show an indefinite number of classes of waves. When the mean of the day is used, as, for example, the mean daily temperature, there is usually found one class of waves with maxima at intervals of two or three days, a second class with maxima at intervals of five to seven days and a third class, a fourth, etc., with maxima at progressively longer intervals. Fig. 128 shows a plot of the temperature in Buenos Aires smoothed in this way. Curve one shows a plot of the observed temperature at 8 A. M. and 8 P. M. in Buenos Aires for March 27 to April 30,

1921. Curve two shows the mean of each 3 consecutive observed values, curve three the means of 5, curve four the means of 9, curve five the means of 13, curve six the means of 19 and curve seven the means of 25 observed values, or 12½ days. It is seen *from the plot that curves one and two show a set of waves with maxima at intervals of two or three days numbered 1, 2, 3, etc.* In curves three and four these maxima of greater frequency are smoothed out and there appear waves with maxima at intervals of from five to seven days, *a, b, c*, etc.; in curves five and six these waves in turn are smoothed out and there remain maxima and minima with frequency of about a month, *A, B*, etc. A further separation can be made by subtracting the values giving the

FIG. 129 FIG. 130



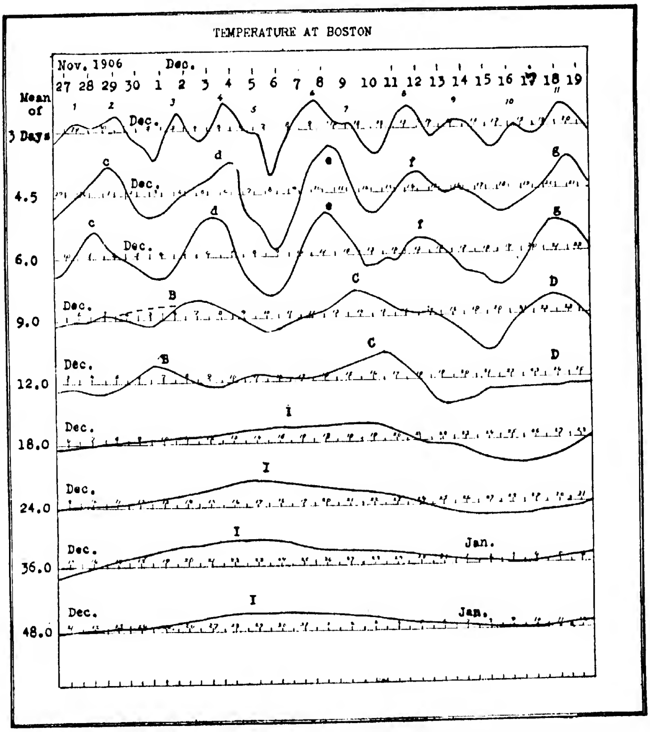
Illustrating Process of Harmonic Analysis

best five to seven day waves from the observed values, for obtaining class I; then for class II subtracting the values giving the thirty day waves from the values best showing the five to seven day waves, etc. In this way were obtained the curves indicated by class I, class II, and class III, in Fig. 142.

(3) The smoothing may be done by harmonic analysis, beginning at any point p (see Figs. 129 and 130), and taking a trial period of any length, a summation is made of the product of all the observed values by the cosines of consecutive angles and then of the sines of these angles. The summation of one set gives a value equivalent to the length of the line a in Figs. 129 and 130 and the summation of the other set gives a value equivalent to b. Beginning next at a point g a little later in time a second summation gives values equivalent to the lines a' and b'. Proceeding thus, a maximum value of a and a zero value of b is found at a point r. There is, however, a displacement or retardation of the maxima equal to one half of the length of the assumed period

which needs to be corrected for. Fig. 131 gives an analysis for the temperature of Boston, Massachusetts, made in that way, using the summation of the cosine terms only (see Appendix C). Curve one in the figure was computed from a trial period of 3 days, curve two from a trial period of 4½ days, curve three

FIG. 131



The Temperature at Boston, Mass., Analyzed into Waves of Different Classes by Harmonic Analysis

from a trial period of 6 days, curve four from a trial period of 9 days, curve five from a trial period of 12 days, curve six from a trial period of 18 days and curve seven from a trial period of 24 days, curve eight from a trial period of 36 days and curve nine from a trial period of 48 days. It is seen that here also only a few classes of waves are shown, the first represented by curve one,

the second by curve three, the third by curve five and the fourth by curve seven.

(4) A partial analysis of the observations can be made by taking differences at longer and longer intervals. If, for example, it is desired to separate the daily wave of temperature from a series of observations, this may be done by taking temperature changes at intervals of twenty-four hours. Thus, taking the change from 1 A. M. of one day to 1 A. M. of the next, then from 3 A. M. of the first day to 3 A. M. of the second, etc., a series of changes is obtained freed from the diurnal period. If there is a series of waves freed from the diurnal period, like those shown in Fig. 128, differences at intervals of one day will show changes due to waves somewhat longer than one day, but the resulting waves will be waves of great frequency only slightly affected by the longer waves; but, if changes be taken at intervals of three days, which is near the length of the more frequent waves, these smaller waves of about three days will be in part eliminated and the changes will be due chiefly to the waves of five to seven day frequency.

Comparing the different classes of waves at stations near together arranged in the order of longitude, it is found that the waves of different frequency progress from place to place with different speeds, the most frequent, or shorter, waves moving fastest and the longer waves more and more slowly in inverse proportion to the wave frequency. This important fact proves the independence of each of the different classes of waves.

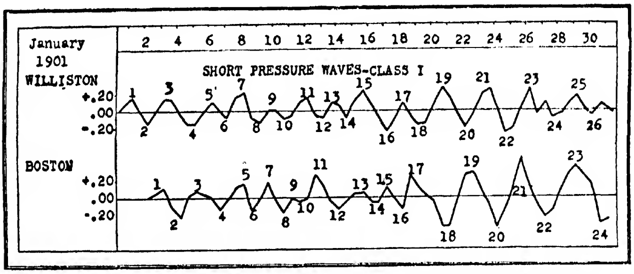
The different rates of progress of different classes of temperature waves is illustrated in Fig. 126, in which the shorter waves require about five days to pass from Fort Assinniboine, Montana, to Eastport, Maine, while the minimum temperatures of the prolonged period of cold felt at Fort Assinniboine near the middle of January were not felt at Eastport until the end of the month, and the warm period observed at Fort Assinniboine between January 26 and 31 was not felt at Eastport until between February 6 and 9.

Fig. 127, taken from the *Monthly Weather Review* of April, 1907, illustrates the same thing for pressure. It is plotted from observations of pressure from January 1 to February 9, 1901, at Williston, North Dakota, Duluth, Minnesota, Chicago, Illinois, and Boston, Massachusetts. In this plot, vertical lines represent differences of one day and horizontal lines differences of one tenth of an inch of pressure. The continuous curves show the observed fluctuation of pressure. The different curves show that the

maxima and minima of pressure indicated by the numerals 1, 2, 3, etc., move very rapidly from west to east, taking about three days to move from Williston to Boston.

If, however, smooth curves derived from the means of three days, like those shown by the broken lines, be plotted through these rapid fluctuations and the maxima and minima in the smoothed curve are marked *A*, *B*, *C*, etc., there is evidence that, underlying these rapid fluctuations of pressure, there are slower oscillations which move more slowly than those marked with the numerals. The time taken for the maxima and minima marked *A*, *B*, *C*, etc., to move from Williston to Boston is about five days. This time is nearly twice as great as that required for the more

FIG. 132



Comparison of Short Period Pressure Waves at Williston and Boston

rapid fluctuations, marked 1, 2, 3, etc., to traverse the same distance.

By subtracting the values used in plotting the curve *A*, *B*, *C*, etc., from the observed values, the shorter fluctuations are separated from the longer and may be plotted separately, as in Fig. 132. Then by plotting the readings of the curve *A*, *B*, *C*, etc., as in Fig. 133, it is seen that the maxima are from five to seven days apart, and by taking the means of each consecutive six values smooth curves are obtained like the broken curves in Fig. 133, which show still longer oscillations, and slower moving waves requiring about ten days to move from Williston to Boston.

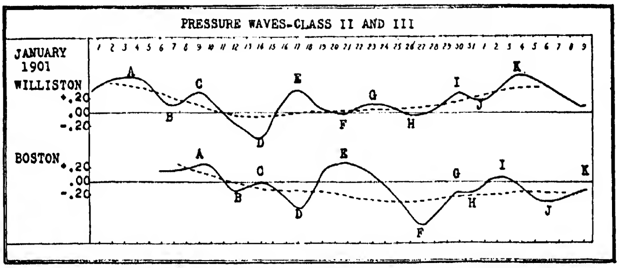
Analysis of the observed values of temperature at thirteen widely separated stations in the United States were carried out consecutively for three years, 1897, 1898 and 1899. The selected stations were Boston, Massachusetts; Hatteras, North Carolina; Key West, Florida; Buffalo, New York; Chicago, Illinois; Little Rock, Arkansas; Galveston, Texas; Williston, North Dakota;

Denver, Colorado; El Paso, Texas; Salt Lake City, Utah; Seattle, Washington; Los Angeles, California.

The waves were arranged in different classes and for each class the departures from the mean were plotted on charts, one chart for each day.

Fig. 134 shows the charts from February 23, 1899, to March 2, 1899, made from the waves of greatest frequency with maxima at intervals of two or three days. The residuals obtained after eliminating the other classes of waves were used for this purpose and lines of equal value were drawn. It is seen from these charts that the maxima and minima first appear in the northwestern part of the United States and move southeastward, passing off

FIG. 133



Pressure Waves of 5 to 7 Day Period at Williston and Boston

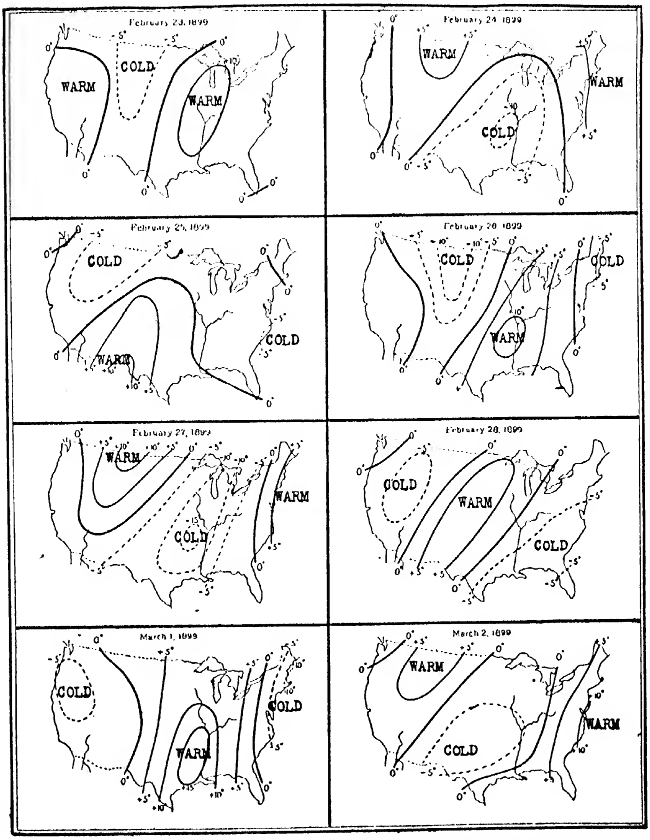
the Atlantic coast in from two to two and a half days after first appearance.

Fig. 135 shows the departures for the waves of class II, like those shown by curve *A*, *B*, *C*, etc., in Fig. 133. These charts, one for each day, cover the interval for February 25, 1899, to March 4, 1899, and show that the maxima and minima begin in the northwest and progress southeast, but take about six days to cross the United States.

In the waves of class III, the progressive movements of which are shown in Fig. 136, maxima and minima were about a month apart and these progressed so slowly that charts every four days were sufficient to show the progress of the waves. These cover the interval from February 2, 1899, to March 2, 1899, and show the progressive movement of one maximum and one minimum. The maximum moved southeastward, from Montana to the Carolina coast, taking about sixteen days, while the minimum appeared in the region of Montana and moved nearly due east,

taking sixteen days to reach the New England coast. The normal movement of all the various classes of waves is from northwest toward southeast in the United States.

FIG. 134

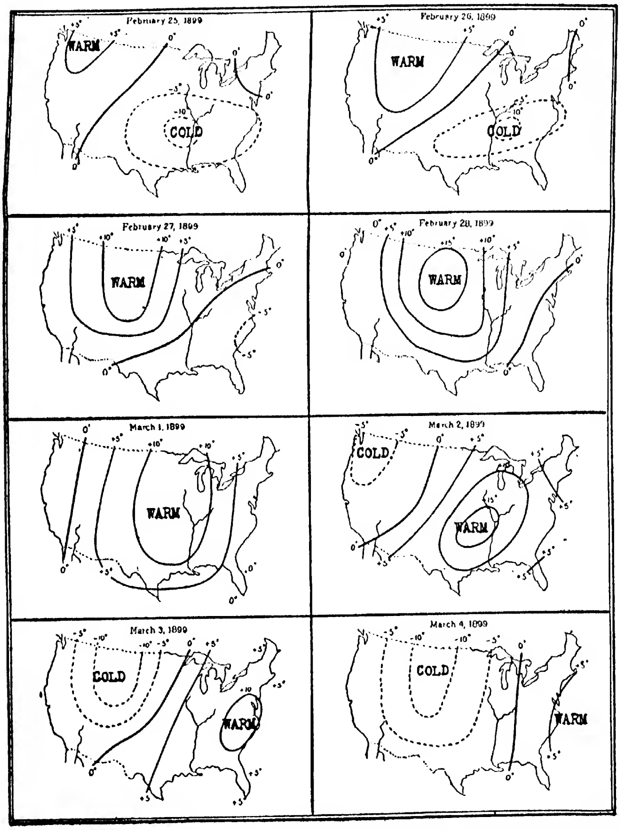


Progress of Temperature Waves of 2 to 4 Days Period in the United States

Longer waves move even more slowly and may occupy weeks in crossing the United States. The velocity of travel of the different classes of waves appears to be approximately inversely proportional to the frequency of oscillation at any one place, but the

data at hand do not indicate an exact ratio. When frequency or time of oscillation are plotted as abscissas and velocity of

FIG. 135



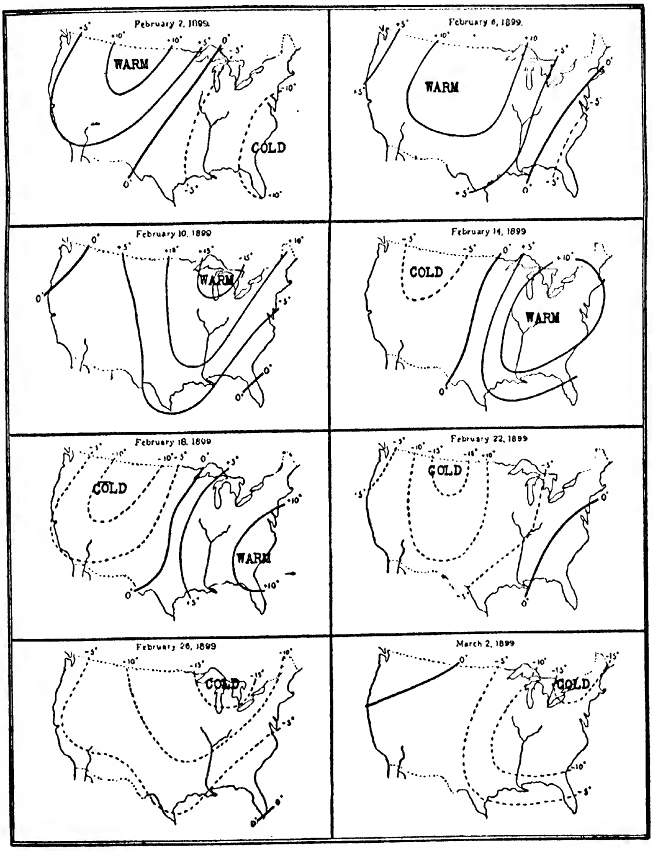
Progress of Temperature Waves of 5 to 7 Days Period in the United States

progress as ordinates, a flat curve is obtained of the nature of a parabola.

The actual distance in space between the maxima and minima of these waves is so great that even the grand expanse of the United States is not sufficient to measure it. Between the crests

of the shorter waves of two to three days' frequency there appears to be a space of about three thousand miles, while in the next class of waves of five to seven days' frequency the width of a

FIG. 136



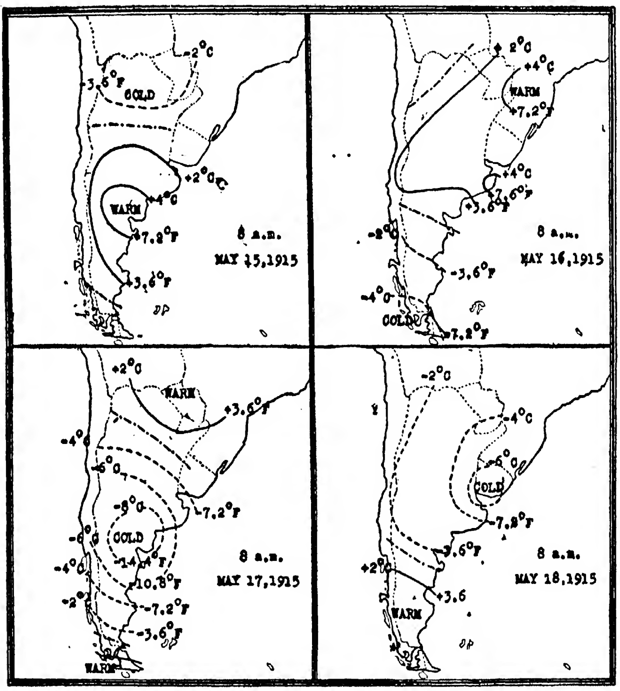
Progress of Temperature Waves of 25 to 35 Days Period in the United States

half-wave, from maximum to minimum, is over two thousand miles, and in the third class of waves of about thirty days' it is even longer.

Similar analyses of the temperature and pressure have been

made for Argentina. Charts made like those for the United States show like results as to the velocity, character and distance apart of the various classes of waves (see "Historia y Organizacion del Servicio Meteorológico Argentino," 1915, p. 152). The only difference in the southern hemisphere is that the waves, in-

FIG. 137



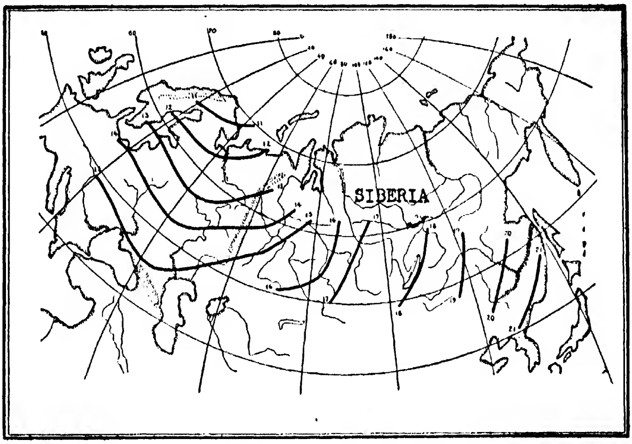
Departures from Normal Temperature in Argentine, May 15 to 18, 1915, Showing Progress of a Cold Wave

stead of moving from northwest to southeast, move from southwest to northeast. Appearing first in Patagonia, they move northeastward to the Atlantic coast or to southern Brazil. The charts in Fig. 137 show the progress of a cold wave of class I which appeared in the extreme south of Patagonia on the morning of May 16, 1915, reached southern Brazil on the morning of

May 18. The waves of classes II, III, etc., move in the same general direction, only much more slowly. In each case the movement is from the pole toward the equator with a drift from west, probably due to the general atmospheric circulation. These waves will be considered later when dealing with solar phenomena.

In Eurasia (Europe and Asia) the cold and warm waves appear in the extreme north, at times north of 70° latitude, and move southeastward to the Pacific coast. Fig. 138 gives an example

Fig. 138



Progress of a Cold Wave in Siberia

quoted by Exner [2] in which the cold wave was first observed in the extreme north of Norway near latitude 70° and moved southeastward across Siberia to the Pacific coast, between latitudes 40° and 47°. Had observations been available it could probably have been followed also across southeastern Asia.

In studying periodical phenomena, I found that many, or most, of the weather waves which reach northwestern Europe have their origin in the neighborhood of Greenland (*American Journal of Science*, Vol. 18 (March, 1894), p. 223).

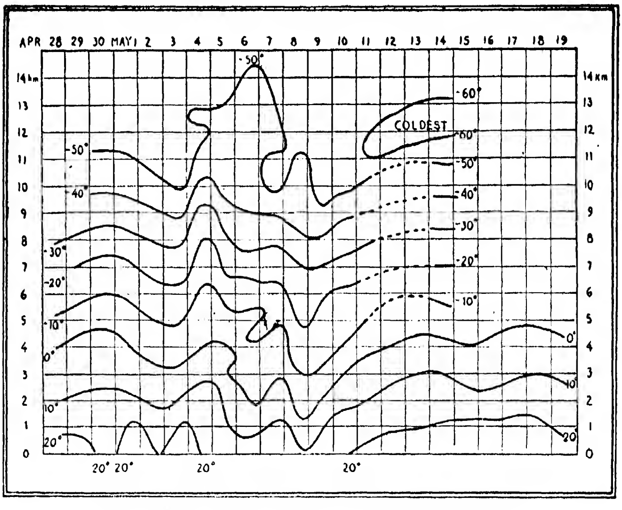
If pressure and temperature changes be taken for intervals of a few hours (3 to 6 hours) and corrected for the normal daily changes, the process will partly separate the very short waves

[2] Exner, Dr. Felix M., "Anschauungen über kalte und warme Luftströmungen," *Geografiska Annaler*, 1920, H. 3, p. 225.

from those of longer oscillations and the shorter waves will be found to move much more rapidly. It is for this reason that Ekholm found in Europe and Hanslik in the United States that the short-period barometric and temperature changes moved away from the changes which accompany the movements of cyclones and anticyclones as seen ordinarily on the weather map.

The results of the soundings made with instruments lifted by kites or sent aloft on sounding balloons have shown that these

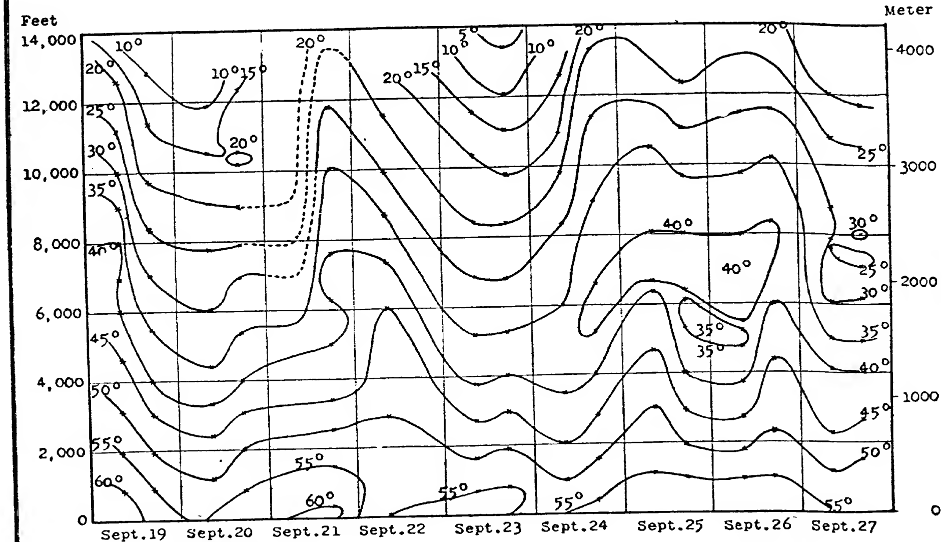
Fig. 139



Lines of Equal Temperature Heights above St. Louis

temperature waves are not merely surface phenomena, but extend aloft at least to the top of the *troposphere* 5 to 6 miles above the earth's surface, embracing about eight tenths of the whole atmosphere. Fig. 139 shows a plot of the observed temperatures at various heights on successive days at St. Louis, and Fig. 140 shows a plot for a point in northern Europe. It is seen that in general the isotherms rise and fall together, so that the cold days at the ground are cold up to a height of about 7 miles (11 km.) and the warm days at the ground are also warm at all heights up to 7 miles. In fact, these changes from warm to cold appear to be larger at heights of from 3 to 5 miles (5 to 8 km.) than at the surface.

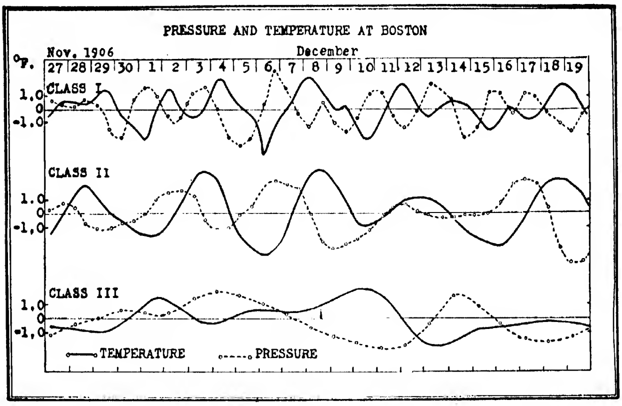
Fig. 140



TEMPERATURES AT VARIOUS HEIGHTS ON SUCCESIVE DAYS-AFTER C.K.M.DOUGLAS
September 19 to 27, 1918

It remains now to consider the relation of the pressure and temperature waves to each other. In Fig. 141 are plotted three different classes of temperature and pressure waves. The temperature waves are indicated by continuous lines, while the waves of atmospheric pressure, derived in the same way for the same station, are plotted in broken lines. It is seen that in general the temperature and pressure go opposite to each other and a marked depression of temperature, as on December 6, at Boston (Fig. 141) is accompanied by a marked elevation of pressure;

FIG. 141



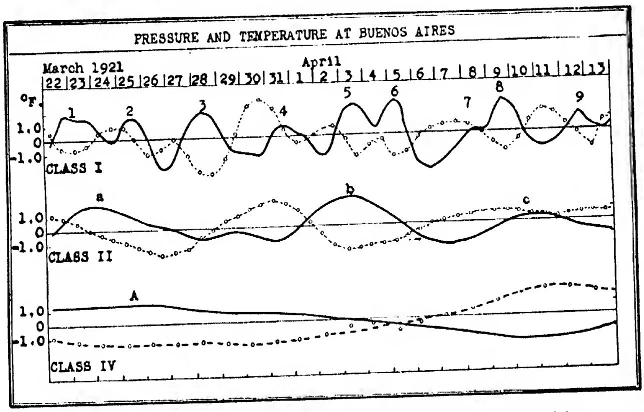
Temperature and Pressure at Boston Showing Opposition

but the maxima and minima of the waves are not coincident in time. In the case of the shorter waves, indicated as Class I, the maxima and minima of pressure lag from six to twelve hours behind the corresponding minima and maxima of temperature; while, in the case of the longer waves, indicated by Classes II and III, the lag is from one to two days. Fig. 142 is derived from observations in Buenos Aires and shows that these relations are almost exactly the same at Buenos Aires in the southern hemisphere as at Boston in the northern.

In order to compare the temperature with the winds the observations of direction and velocity made at the Chacarita Observatory in Buenos Aires from March 1, 1921, to May 5, 1921, were analyzed into two components of motion, one along a north-to-south line, that is from equator to pole, and the other

along the meridian from east to west. Dealing only with the north to south air movement, calling the movement from the equator plus and from the pole minus, a series of values was obtained that varied in the same manner as did the temperature. Using two observations a day, namely 8 A. M. and 8 P. M., and analyzing in the same way as for the temperature, shown in Fig. 128, a similar series of values was obtained. The observations of atmospheric pressure at 8 A. M. and 8 P. M. for the same interval were treated in the same way and the three classes of

FIG. 142



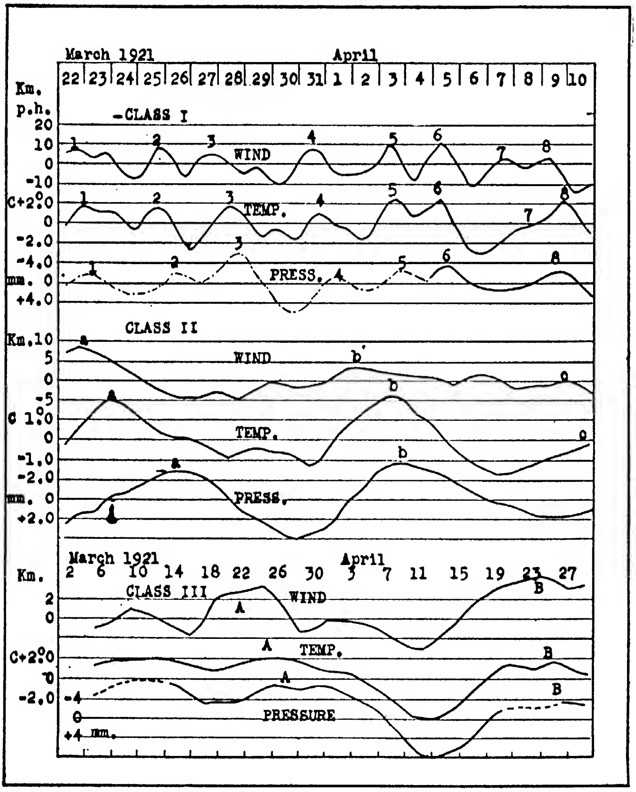
Temperature and Pressure at Buenos Aires Showing Opposition

waves derived from these plots are given in Fig. 143. To facilitate comparison, the pressure in this plot is inverted, so that low pressure is above the zero line and high pressure below. It is seen that equatorial winds, represented by values above the zero line, accompany high temperatures; and polar winds, represented by values below the line, accompany low temperatures. It will be noted, however, that the maxima and minima of the wind movement precede the maxima and minima of temperature, while the minima and maxima of pressure follow the maxima and minima of temperature.

Observations in the upper air made by means of kites and balloons show that the air rushing toward the equator in front of a cold wave is a thin wedge and the high velocity is clearly the result of air descending from above, while at the same time

advancing from the direction of the pole. In fact the clear dry air throughout the cold area indicates a descent. The observations with sounding balloons at St. Louis (*Annals of the Astronomical Observatory of Harvard College*, Vol. 47, Part 1) show

Fig. 143



North-South Wind Components Compared with Temperature and Pressure of Buenos Aires

that the lowest temperature in the upper air is to the north of the area of high pressure and from that height there is apparently a descending stream of air moving from the northwest which reaches the earth's surface in the low pressure along the advanc-

ing edge of the cold air. The heating of the descending air by compression is more than offset by the change of latitude.

This great mass of cold air proceeding equatorward produces a marked contrast of temperature along its front, on the side toward the equator as well as on its eastern front. There is a crowding of the lines of equal temperature together, causing differences of pressure by differences of density and an increased wind movement. In the lower atmosphere the cold air presses in toward the warmer tending to lift it, but in the upper atmosphere, where there is little friction, the air movement under the influence of the earth's rotation quickly becomes nearly parallel to the lines of equal temperature and pressure aloft and hence nearly at right angles to the temperature gradients which are directed inward from the warm area toward the cold. In discussing the cloud observations made by me at Blue Hill, I found a marked tendency of the highest clouds to move at right angles to the temperature gradient when the gradient was well marked as shown by the following results:

TABLE X

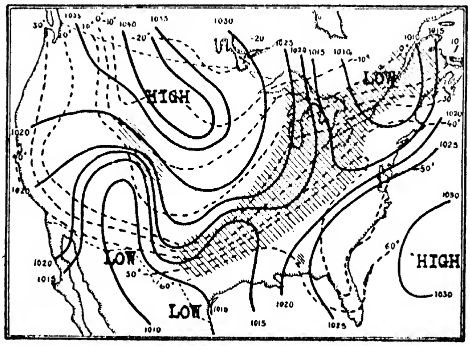
Temperature Gradient from	*Frequency of Cirrus Clouds from*							
	S	SW	W	NW	N	NE	E	SE
SW	0%	0	25	75	0	0	0	0
S	4%	8	67	22	0	0	0	0
SE	0%	53	37	10	0	0	0	0

The temperature gradient was that observed at the earth's surface and since the gradient is measured at right angles to the temperature lines, a gradient from southwest indicates that the temperature lines ran from northwest to southeast and that 75 per cent of the cirrus moved parallel with the temperature lines. On the other hand, when the temperature lines ran from southwest to northeast (with a gradient from southeast) the cirrus moved from southwest. Moreover, the velocity of the cirrus increased with the steepness of the gradient. In measuring steepness of gradient the unit of distance was taken as 250 miles. When the distance between the nearest 10° F. isotherms was twice this amount, or more, the gradient was recorded 0; when between once and twice the distance, it was recorded 1; when there were two isotherms within the 250 miles, the gradient was recorded 2; when three isotherms it was recorded 3, etc. From these data and the observed cloud movements reduced to miles per hour the following results were obtained:

Steepness of Gradient......................	*0*	*1*	*2*	*3*	*4*
Mean velocity of cirrus (miles per hour)....	45	54	62	78	94

From these results, it is evident that temperature contrasts in the lower air are attended by rapid movements of the upper currents along the direction of the isotherms and at right angles to a line passing from the cold area toward the warm area. This circulation develops a centrifugal force which tends to carry the air away from the cold area and, hence, lowers the pressure on that side of the cold area and within the area of temperature

FIG. 144



——— Pressure Lines ---- Temperature

Weather Map, 8 a. m., Feb. 16, 1910, United States. Shaded Areas Show Region Within Which Rain or Snow was Falling

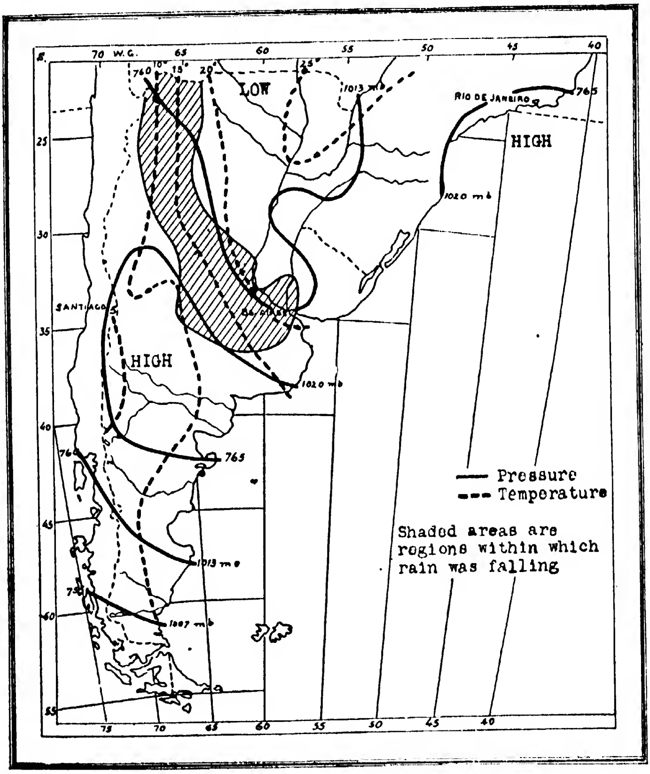
contrasts. The theory of this air movement is treated fully in the chapter on cyclones and anticyclones.

Both the centrifugal force of the circulating winds and the lifting of the warmer air by the underflow of cold winds tend to develop strong ascending currents along the equatorial and eastern side of the cold wave and thus cause ascending currents, clouds and precipitation from the dynamic cooling of the ascending and expanding air. In the United States, Argentina, and probably in all regions outside the tropics, rain falls within these belts of temperature contrast between the warm and the cold wave.

Fig. 144 shows an example of the area of falling rain and snow in the United States at 8 A. M. on February 6, 1910, and Fig. 145 gives an example in Argentina at 8 A. M., March 25, 1921. The area of precipitation is indicated in each case by the shaded area.

When the time of rainfall is indicated on a plot like that of curve one in Fig. 128, it is seen that the rain comes generally when there is rapidly falling temperature after a period of higher temperature and not with rising temperature. If it were possible

FIG. 145



Argentine Weather Map. 8 a. m., March 25, 1921

to make a plot of this kind in advance of its occurrence, it would be possible to anticipate the time of occurrence of most of the rainfall.

From a survey of the various facts presented above, one is led to the conclusion that the primary cause of all these different effects is the great mass of cold air moving under the in-

fluence of gravity from high latitudes and from the coldest parts of the land or water areas toward the equator, but which at the same time are carried eastward by the general atmospheric drift. These cold masses at times undoubtedly come from the region of the pole itself but probably in general from the center of greatest cold on the continental land masses. The warm waves which follow them are secondary because they drift in the same direction and are probably caused in part by the air heated by compression as it descends in the high pressure in the rear of the cold wave. This warmed air moves poleward to ascend in an area of low pressure advancing in the front of a second cold wave following the one under consideration.

As explained above, the high wind velocity along the advancing edge of the cold wave lowers the pressure in that part of the cold wave and, hence, the maximum pressure is found on the polar or on the western side of the cold wave. This matter is explained more fully in Chapter VIII.

CHAPTER V

PRESSURE AND THE WEATHER

SUMMARY

Different types of distribution of pressure are considered and their characteristics explained.

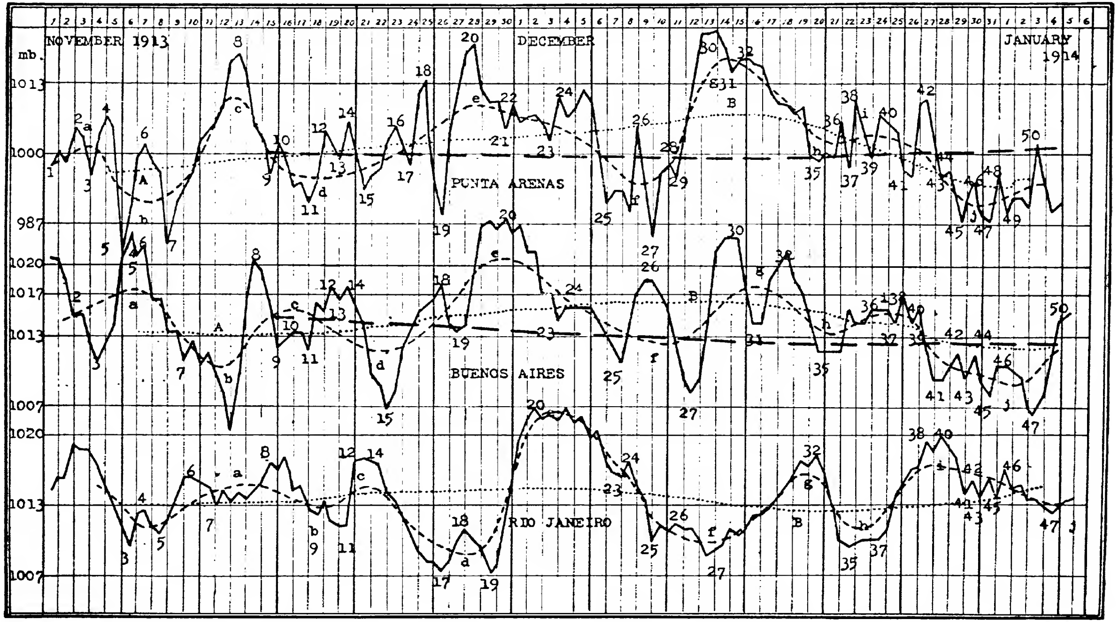
Differences of temperature over large areas, as between equator and pole, continent and ocean and between large masses of air changing position in latitude cause both pressure differences and wind; but the temperature at any one place may be so affected by local conditions as not to be a measure of the general distribution of temperature in that region. The pressure is a more reliable guide to general conditions than the temperature observed near the earth's surface, because the pressure is less affected by local conditions and depends on a summation of the conditions of the whole atmosphere above the place.

The pressure on a mountain top depends on the pressure at sea level and the mean temperature of the air column up to the top of the mountain; but, as it is usually very difficult to observe the mean temperature up the side of a mountain, Dr. Julius Hann found it convenient in many cases to compute the mean temperature of the air column from the differences in pressure. So, in studies of meteorological sequences it is frequently convenient to start with observed differences of pressure.

Fig. 127 shows a plot of pressure waves in the northern hemisphere and Fig. 146 gives a similar plot for the southern hemisphere. This plot was derived from observations at 8 A. M. and 8 P. M. at Punta Arenas, 53° 10′ S., 70° 54′ W.; at Buenos Aires, 34° 36′ S., 58° 22′ W., and at Rio de Janeiro, 22° 54′ S., 43° 10′ W. It is seen from the plot that the waves of greater frequency like those marked 1, 2, 3, etc., take usually about three to four days to move from Punta Arenas to Rio de Janeiro, while the larger smoothed waves *a, b, c,* etc., take from six to eight days.

When observations of pressure from many places, not too far apart, are plotted on a chart or map and lines of equal pressure

Fig. 146



Pressure Changes Showing Wave-like Oscillations in the Pressure in South America, Nov., 1913, to Jan., 1914

(isobars) are drawn, it is found that these lines assume a variety of forms, each of which has an interesting relation to weather conditions. Abercrombie was one of the first to classify these various shapes.

The principal forms assumed by isobars may be described as circular or elliptical isobars, U-shaped isobars, V-shaped isobars, straight isobars, troughs, wedge-shaped and "cols." Troughs are formed between two adjacent areas of high pressure; "cols," or collars, of somewhat higher pressure between two adjacent areas of low pressure.

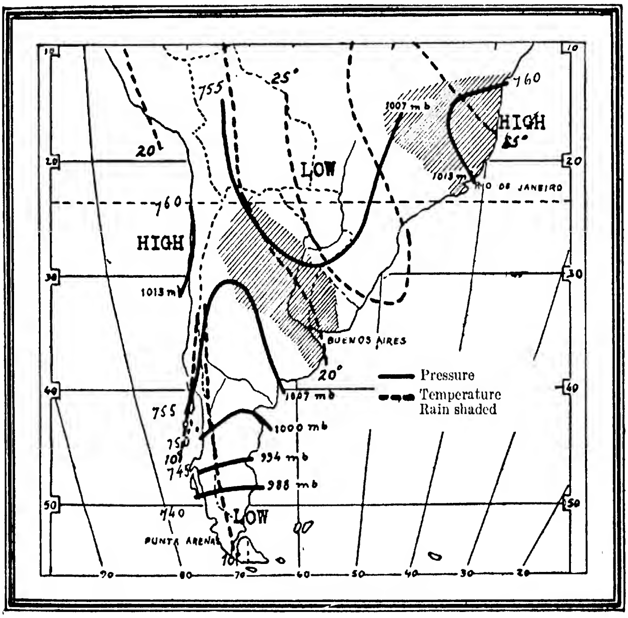
Each particular class of isobars is associated with a set of weather conditions peculiar to itself. Circular and elliptical isobars are associated with well developed cyclones and anti-cyclones which will be treated later. Straight, nearly parallel isobars are associated with settled weather. When the atmosphere is but little disturbed by moving waves of temperature and pressure the isobars lie nearly parallel with the lines of latitude, the pressure decreasing from about latitude 30° toward the equator on one side and toward the poles on the other. This condition is especially characteristic of the southern hemisphere. When waves of falling pressure of moderate intensity are progressing equatorward the straight isobars are bent somewhat and form U-shaped depressions. This is the most common type in Argentina, an example of which is shown in Fig. 147. It will be seen that the isobars in extreme southern Argentina are nearly straight lines; in central Argentina the isobars bend upward in a large loop or an inverted U with the rounded part to the north; while farther north the isobars dip southward to form a looped U-shaped depression with the rounded part to the south. Usually the temperature is rising to the east of these loops and falling to the west. There is some cloudiness in the east and perhaps local rains, but heavy rain or general rain over large areas is very rare.

The V-shaped depression is usually formed on the equatorial side of large oval isobars and is of frequent occurrence in the United States and Europe. It shows marked contrasts of weather on its east and west sides. On the east side, there are brisk equatorial winds accompanied by increasing cloudiness, and the temperature is above the normal of the time of the year with heavy rain near the trough of the V. On the west side are found polar winds with low temperature and clear or clearing skies. Fig. 148 shows an example of one of these depressions near Great Britain on the morning of October 9, 1921.

An inverted V (Λ) is the form assumed by this type of isobar

in the southern hemisphere, while in the northern hemisphere the inverted V (Λ) is called a wedge. In the wedge the weather conditions are the reverse of those in the V, the pressure is higher within the wedge than on either side; it is clear and cold in front and warm and cloudy or rainy in the rear. These two types of depression, the U and the V, represent immature or undeveloped cyclones within larger cyclones.

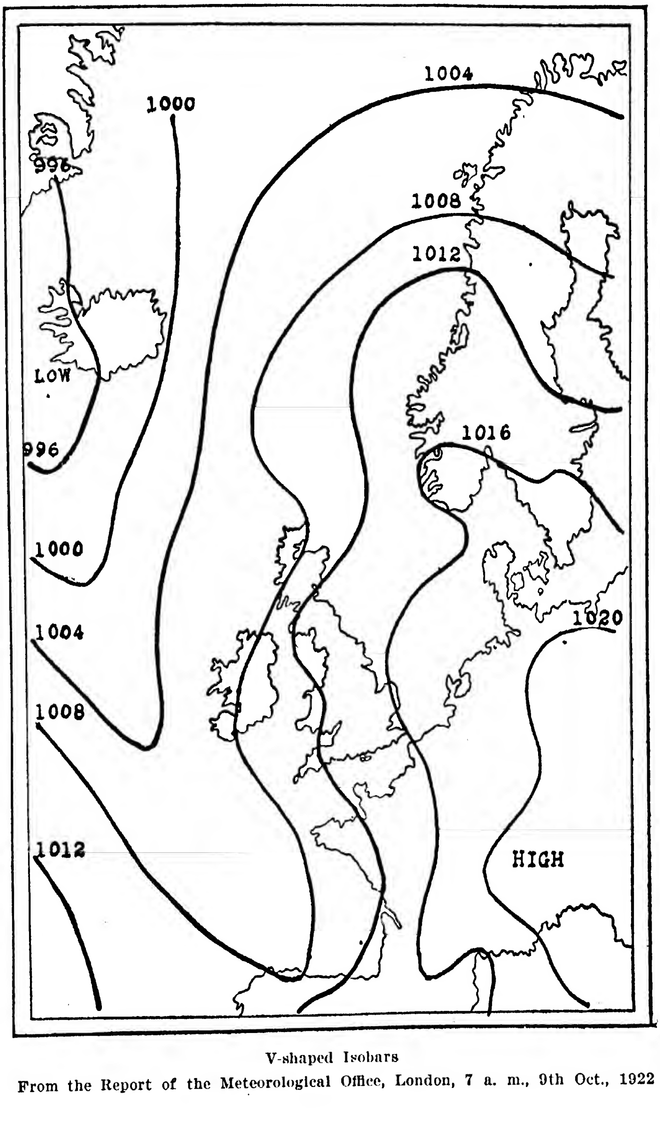
FIG. 147



Weather Map of Argentina. 8 a. m., March 25, 1921

A collar of somewhat higher pressure between two centers of low pressure is illustrated in Fig. 147. Within the area of the "col," as it was called by Abercrombie, there is a descent of air because the air is blowing outward in both directions, the sky is usually blue, the air dry, the sunshine bright with but little wind, and at night there is a strong radiation and a low temperature at the earth's surface, sometimes with frost. A marked example of such a case was observed in New England in

Fig. 148



V-shaped Isobars

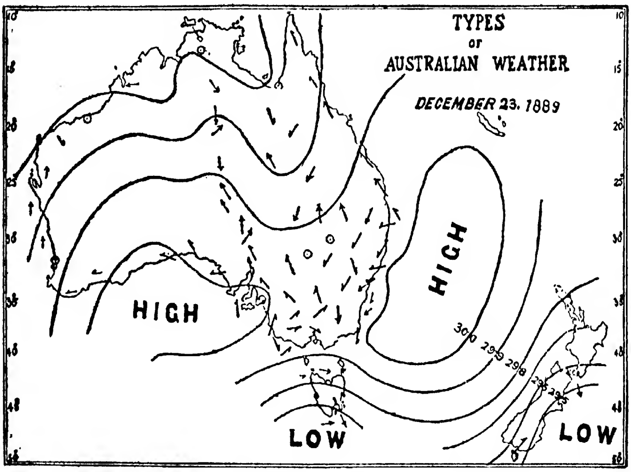
From the Report of the Meteorological Office, London, 7 a. m., 9th Oct., 1922

1886, when frosts were observed even in August (*Science*, Vol. VIII, pp. 233, 281). This type of fine weather is sometimes called "a weather breeder" because it is of short duration and usually followed by a storm.

In a trough, between two areas of high pressure, there are likely to be haze or cloud and temperature above the normal. If there is a marked difference of temperature between the two sides of the trough there is likely to be precipitation. See Fig. 149.

The converging or diverging winds found in U-shaped depressions and V's serve to explain many of the conditions of the

FIG. 149



A Trough of Lower Pressure between Two Highs

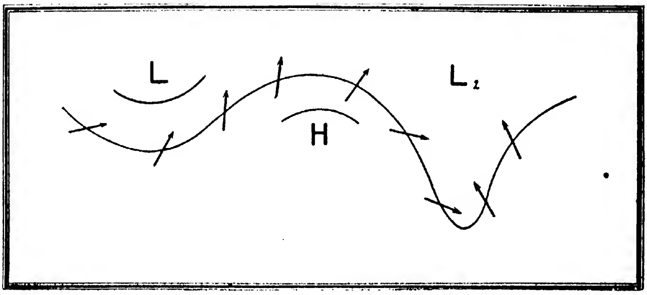
weather. Fig. 150 shows an arrangement in which there is an area (L) with U-shaped isobars, another region marked (H) which takes the form of a wedge and a third marked L_2 which has the form of a V.

In all such depressions as those marked L in Fig. 150 the winds are converging toward the area of lowest pressure, and to permit the lower air to occupy the smaller space which this convergence implies, a part of it must ascend; hence, the air is expanding and cooling and there is condensation of moisture; in general regions of low pressure are regions of converging winds and regions of high pressure are regions of diverging winds

where the air is descending, and is therefore dry and the sky cloudless or nearly so.

As a rule isobars concave to the low pressure are regions of ascending currents and clouds or rain, while convex isobars are

FIG. 150



Schematic Drawing Showing Effect of Convex and Concave Isobars on Wind Circulation

regions of descending winds and fair weather. But when there is a difference of temperature on the two sides, as is the case in high latitudes, the ascent is increased on the warm side and diminished or annulled on the cold side.

CHAPTER VI

WIND AND THE WEATHER

SUMMARY

The rôle of the wind in producing weather changes is taken up. The ideas of Bjerkness on the conflict between polar winds and equatorial winds are considered and the various changes of temperature, pressure, clouds and rain are explained from the standpoint of conflicting winds.

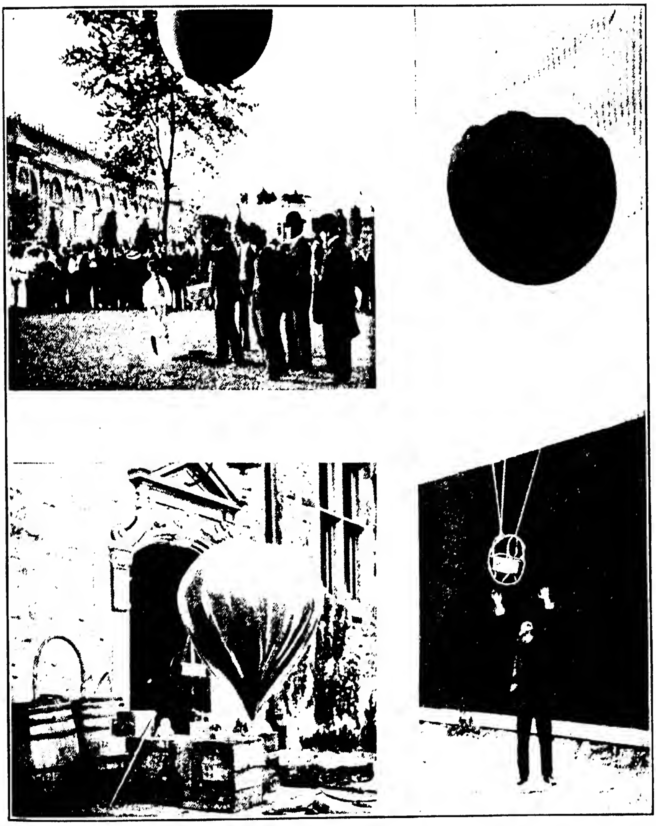
One of the most astonishing attributes of the atmosphere is its extreme mobility. Dust lifted by winds blowing over the arid lands of the Sahara has been followed throughout its entire path as it passed along carried by a great curving stream of air first to the region of the Azores and then to England and northern Europe, which was reached within two days.[1]

On another occasion dust was followed from the Sahara across Italy, the Alps, Austria and Germany to the northern coasts of Europe. Dust clouds thrown out from volcanoes in Alaska and from volcanoes in the tropics have been followed for thousands of miles traveling with speeds of from 70 to 100 miles an hour. High clouds have been measured with theodolites at Blue Hill, near Boston, traveling with speeds of more than 200 miles an hour, and aviators in the United States flying at a height of about 5 miles in machines having a velocity of nearly 100 miles an hour have been carried backward by the winds at that height, although the aviator himself was flying directly into the wind.

The ceaseless roving of the wind has nowhere been more beautifully expressed than by Dr. Buist in the following words:

"It is the girdling, encircling air that makes the whole world kin. The carbonic acid with which to-day our breathing fills the air, to-morrow seeks its way around the world. The date trees that grow around the falls of the Nile will drink it in by their leaves; the cedars of Lebanon will take of it to add to their stature; the coconuts of Tahiti will grow rapidly upon it; and the palms and bananas of Japan will change it into flowers. The oxygen we are breathing was distilled for us some short time ago

[1] Lempfert, R. G. K., *Meteorology*, p. 87. London, 1920.



Filling and Launching Sounding Balloons Carrying Recording Meteorological Apparatus. Experiments at St. Louis in 1904 Under the Auspices of A. Lawrence Rotch, Blue Hill Meteorological Observatory

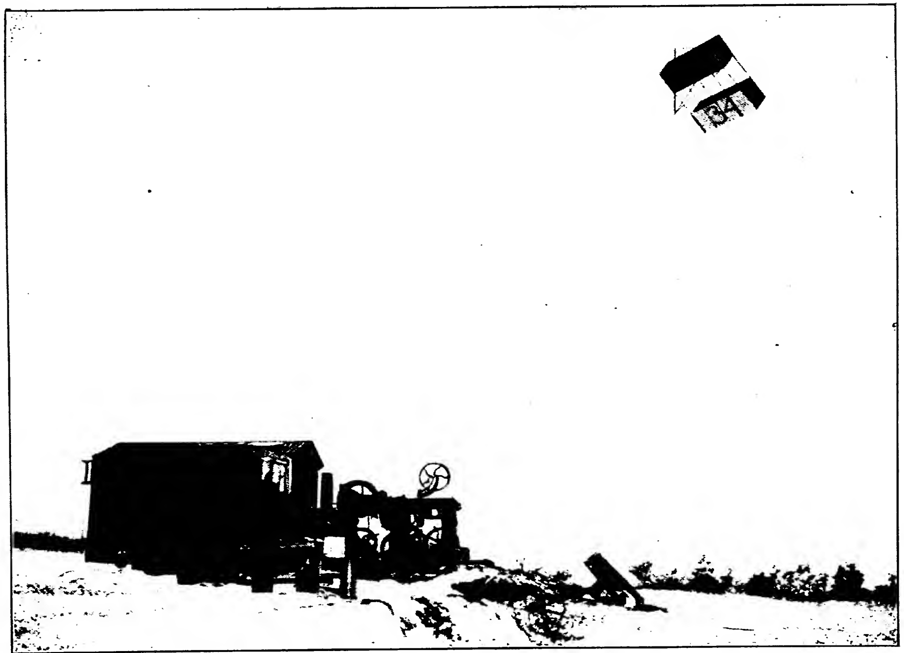


Photo. by Stebbins

Beginning a Kite-flight on Blue Hill. The Clayton-Hargrave Kite Used for Lifting Self-recording Instruments into the Air

by the magnolias of the Susquehanna and the great trees that skirt the Orinoco and the Amazon; the giant rhododendrons of the Himalayas contributed to it, and the roses and myrtles of Cashmere, the cinnamon tree of Ceylon and the forest older than the flood, that lies buried deep in the heart of Africa, far beyond the Mountains of the Moon, gave it out. The rain we see descending was thawed for us out of the icebergs which have watched the Polar-Star for ages, or it came from the snows that rested on the summits of the Alps, but which the lotus lilies have soaked up from the Nile, and exhaled as vapor again into the ever-present air."

CHANGES IN THE VELOCITY AND DIRECTION OF AIR MOVEMENT WITH HEIGHT ABOVE SEA-LEVEL

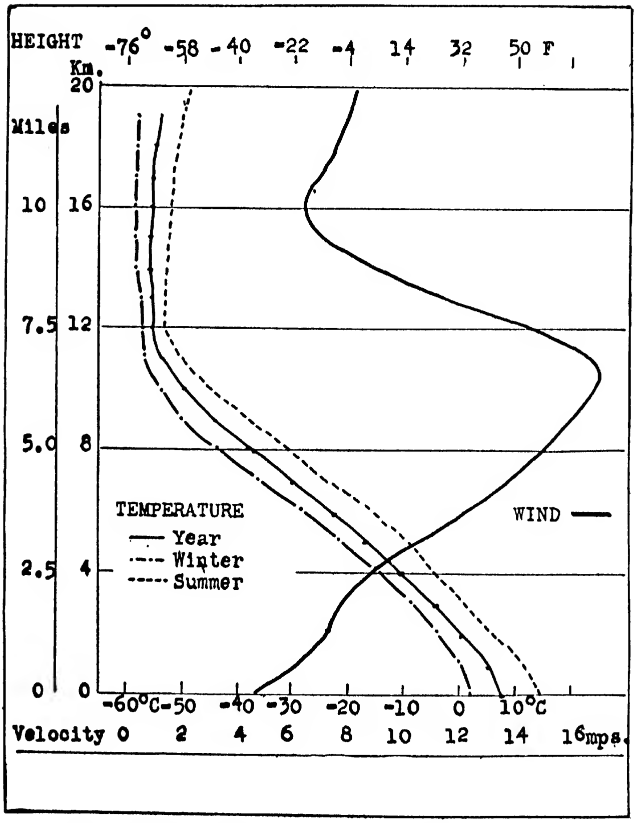
The swiftest winds are encountered in temperate latitudes at a height of about 5 to 7 miles, directly beneath the *stratosphere.* As one rises from the earth's surface the wind velocity increases steadily until it reaches its greatest speed and then decreases suddenly at greater altitudes.

These changes of velocity with height are shown by the heavy line in Fig. 151, which gives mean values of the wind movement derived from a chart published by Captain Dobson in the *Quarterly Journal of the Royal Society,* London. This chart was constructed from hundreds of measurements of the movements of sounding balloons sent up from many stations in Europe (see Plate I). The lighter lines in Fig. 151 show the decease of temperature with height observed in Europe for the year and also for the summer and the winter. A comparison of the two sets of curves shows that the wind increases as the temperature falls, but suddenly at a height of about 7 miles (11 km.), when the temperature ceases to fall, the wind decreases, and at 10 miles (16 km.) the velocity is not much greater than that observed at the earth's surface.

From Fig. 151, it is seen that the wind velocity increased very rapidly at first, because the lower winds are retarded by friction with the earth's surface; but above about 3000 feet the increase is very regular up to the height of about 7 miles (11 km.) and follows a very simple law, namely, *with increasing height above the earth's surface the velocity of air movement increases at the same rate as the density of the air diminishes, so that the product of the velocity and density is nearly constant.* This law was first stated by me in the *American Meteorological Journal* in 1893, and was deduced from a study of cloud movements at Blue

Hill. Egnell found it to be true for cloud movements above Paris as well as at Blue Hill, and it is sometimes called Egnell's law. It is now generally accepted by meteorologists. This law is not general for the whole atmosphere, but is confined to the *troposphere* and is true for the circulation about the wandering cyclones and anticyclones as well as for the general circulation around the permanent cyclones and anticyclones.

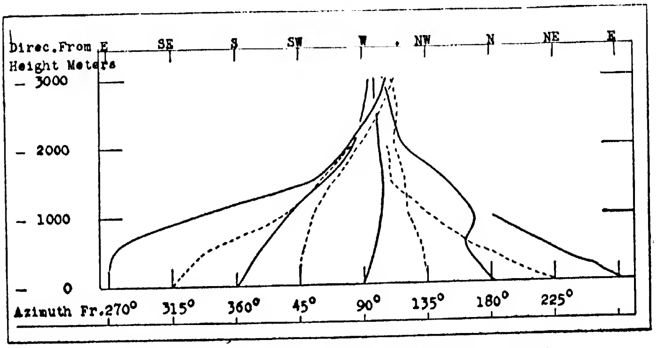
FIG. 151



Change of Wind Velocity and Temperature with Height—Europe

In Fig. 152 is plotted the change of wind direction with height, showing that all surface winds tend to become westerly winds aloft in temperate latitudes. The data were obtained from observations of sounding balloons measured by Fergusson [2] at St. Louis. Southerly winds turn to the right, northerly winds to the left, while easterly winds sometimes turn to the right and

FIG. 152



Change of Wind Direction with Height above St. Louis

sometimes to the left. The same shifting has been found by A. Rankin from pilot balloons sent up near Buenos Aires in the southern hemisphere.

THE WIND AND THE TEMPERATURE

The wind may under certain conditions be considered the cause of temperature changes. When the wind is carried across cold bodies of water or heated plains by the general circulation of the atmosphere, the surface air assumes the temperature of the water or earth and places on the leeward side are heated or cooled. Thus the shores of northern Chile are cooled by winds from the Humboldt current and the northeastern shores of North America by cool waters from the Labrador current. In summer, places on the shores of Argentina are frequently heated by hot winds from the Pampas, and the eastern states of the United States by hot winds from the interior plains. Winds which condense their moisture on the windward side of mountain ranges

[2] Fergusson, S. P.—*Annals of the Astronomical Observatory of Harvard College,* Vol. 47, Part I.

descend on the other side as warm, dry winds, such as the Föhn winds of the Alps, the Chinook winds of the Rockies and the Zondas of the Andes.

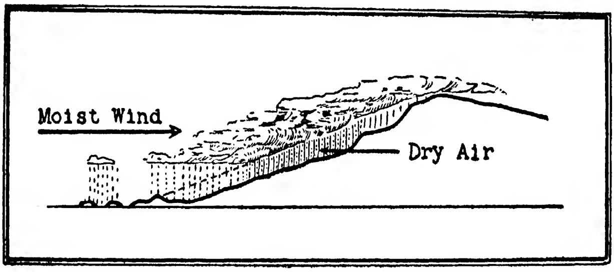
THE WIND AND THE PRESSURE

Moving air acted on by the deflecting effect of the earth's rotation is a cause of a large part of the pressure differences observed over the world, as explained in Chapter I. Wind movements are brought about by temperature contrast, but every movement of the air brings about a new distribution of pressure.

THE WIND AND PRECIPITATION

The winds as causes of precipitation have been especially studied by Bjerknes,[3] although Shaw and others have expressed somewhat similar ideas. By means of a close network of stations in Norway compared with observations at the many stations in Europe, Bjerknes was able to show that warm winds

FIG. 153

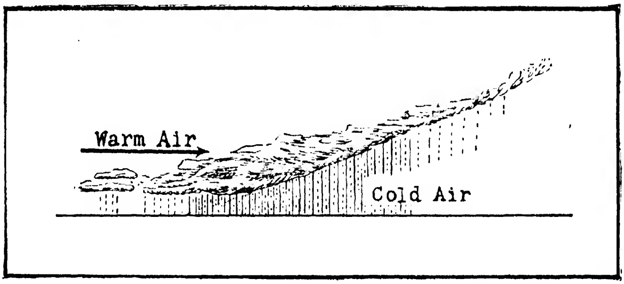


Cloud and Rain Formed in Moist Current Crossing Mountain—After Bjerknes

converging toward colder winds rise above the colder air and their moisture is condensed in the same way as in the air rising over mountain summits. Fig. 153 represents a cross-section in a volume of air passing across a mountain range. As soon as the expanding air is chilled to the point of condensation, cloud formation begins and rain falls when the air reaches the point of supersaturation.

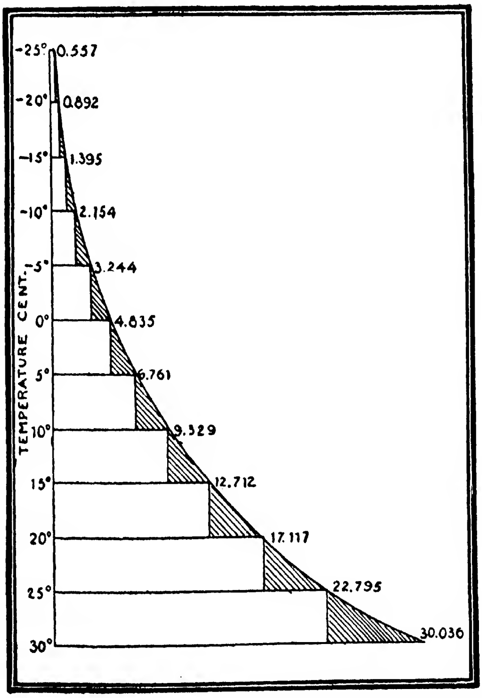
[3] Bjerknes, V.—*Quarterly Journ. of the Royal Meteor. Soc.*, London, April, 1920: also *Nature*, Vol. 105, No. 2643, London, June 24, 1920, p. 522.

FIG. 154



Cloud and Rain Formed in Warm Air Rising Over Cold Current

FIG. 155

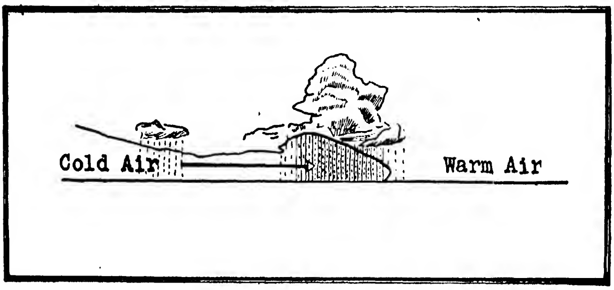


Amount of Moisture Condensed in Steps of 1000 meters—After Humphreys

Fig. 154 shows the horizontal and vertical conditions observed in Europe when a broad stream of warm air converges on to a region of colder air.

As soon as the ascending warm air has cooled by expansion to the point of condensation, cloud formation begins, and rain falls when the air reaches the point of supersaturation. The amount of water vapor that can remain in a unit volume of air at different heights and temperatures with an initial temperature of 30° C. (86° F.) is shown in Fig. 155 for steps of 1000 meters. It is seen that the air is richest in moisture at the lower levels, and consequently after the air is cooled by ascent to the point

FIG. 156



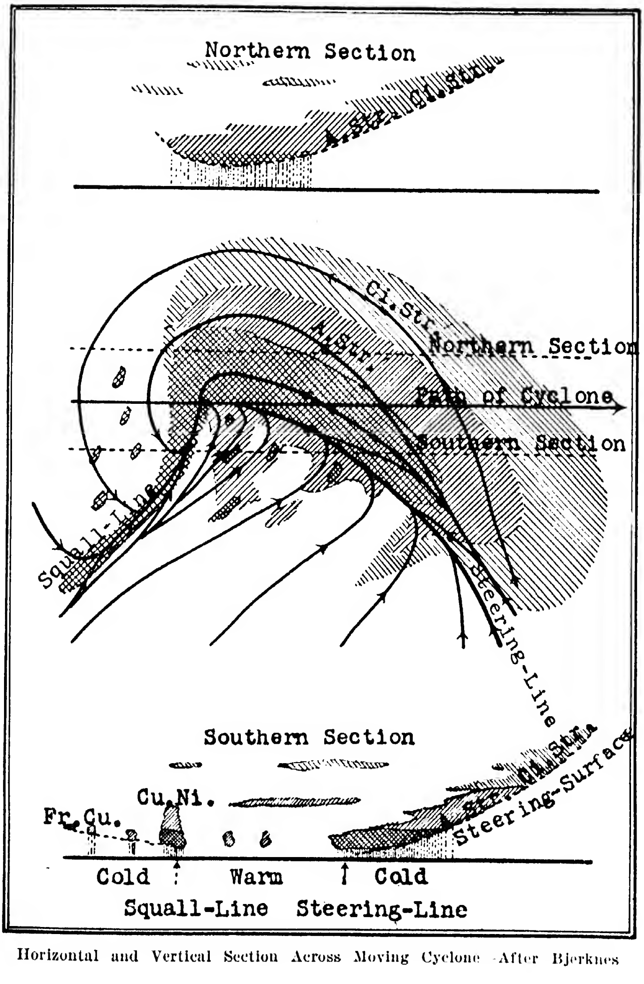
Effect of Cold Air Underrunning Warm Air—After Bjerknes

of condensation the greatest amount of water will fall in the first 1000 meters of further ascent, and less and less will fall at successive higher levels because the capacity of the air for retaining moisture in the form of vapor decreases rapidly with decreasing temperature. For this reason the heaviest rain in an ascending current usually falls on the sides of a mountain below the summit; and when a current of warm air overflows colder air the heaviest rain is near the place of meeting.

The second case investigated by Bjerknes is when a cold current underruns warmer air. Fig. 156 represents a vertical and horizontal section of the moving air as determined from observations in northern Europe. The position of the clouds in relation to the cold air is not such as is usually found in the United States and may possibly need modification for Europe.

A general conception of the wind and rain distribution in moving cyclones as developed by Bjerknes is shown in Fig. 157. Furthermore, Bjerknes conceives the circulation of air in a

FIG. 157



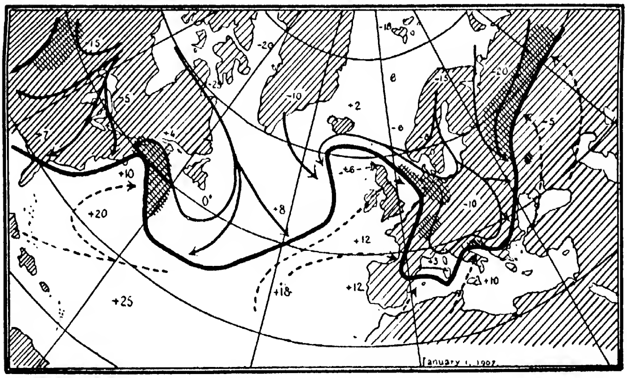
Horizontal and Vertical Section Across Moving Cyclone—After Bjerknes

cyclone to be but a part of a conflict between immense masses of polar and equatorial winds extending entirely around the polar region in temperate latitudes (30° to 60° N.). He says in *Nature* of June 24, 1920:

"It has been found by use of the detailed maps that the line of discontinuity exists even outside the cyclone, passing from one cyclone to the other; they follow each other along a common line of discontinuity like pearls on a string.

"When one has become acquainted with all the signs—direct and indirect—which are seen to indicate the position of a line of discontinuity on the very detailed maps, it proves possible to discover them even on less detailed maps. Fig. [158] shows roughly the course of such a line on January 1, 1907, as it may be drawn upon the Hoffmeyer maps of the Atlantic Ocean for that day. When similar charts are drawn from day to day, as

Fig. 158



Outline of "Polar Front"—After Bjerknes

accurately as circumstances allow, a series of large scale results very distinctly presents itself. Though we have been able to draw the line only half round the pole, there can be no doubt that it surrounds the polar regions as a closed circuit. On the northern side of this line all signs indicate air of polar origin; it has a low temperature for the latitude, shows great dryness, distinguishes itself by great visibility and has a prevailing motion from east and north. On the southern side of the line the tropical origin of the air is recognized by the corresponding signs—its generally higher temperature, its greater humidity, its haziness and its prevailing motion from west and south. There can then be no doubt concerning the origin of the line. Heavy cold air flows out along the ground from the polar regions. It is separated from the overlying warmer air by a surface of discontinuity, the height of which above the ground decreases very slowly until it cuts the ground along our line of discontinuity.

Thus this line shows how far the cold air has succeeded in penetrating; it is a kind of polar-front line.

"Along the whole of this front we have the conditions, especially the contrasts, from which atmospheric events originate the strongest winds, the most violent shifts of wind, and the greatest contrasts in temperature and humidity. Along the whole of the line, formation of fog, clouds and precipitation is going on, fogs prevailing where the line is stationary, clouds and precipitation where it is moving.

"The line has a wavy form, and is in a continuous undulating motion, thereby sweeping over the whole of what is called the temperate zone. The wavy form comes from alternately cold and warm tongues of air, which extend themselves toward the equator or the pole. The whole system is moving from west to east, while the line, at the same time, changes its form, especially when great masses of accumulated cold air are expelled from the central polar regions. The more wavy the form of the line, the more tempestuous and variable is the weather. At northern end of the warm tongues the air motion which characterizes cyclones is recognized and the corresponding areas of rain are seen so far as it has been possible to mark them from the few observations; these are the places of great storms and low barometric pressure. The broad tongues of polar air, on the other hand, bring the clearing up between the successive storms and the corresponding higher barometric pressure.

"Two expanding tongues of cold air may occasionally cut off from its base an interjacent tongue of warm air. Then the storm at the polar end is no longer supplied by warm air, and soon loses its power; this is the death of a cyclone. A tongue of polar air which has extended itself too much towards the tropics may be cut off in a similar way; or as the consequence of a new outbreak of polar air a more retired front may be formed behind one too far advanced. In this way great isolated isles of polar air are formed in lower latitudes; this gives the formation of great anticyclones, which generally bring settled, good weather. Thus anticyclones are born as cyclones die.[4] Cyclone and anticyclone and all meteorological events of the temperate zone are in the most intimate way related to the polar front and its motion.

"This expulsion of great masses of polar air which leads to the formation of anticyclones, also enters as an essential element into the great atmospheric circulation. There is a practically continuous flow of warm air along the ground from the 'highs' of the sub-tropic calms toward the polar regions. This flow concentrates itself in the warm tongues, and continues into the

[4] A different view as to the origin of anticyclones is given in Chapter VIII.

polar regions in upper levels. Here the air is cooled, and eventually reaches lower levels. Thus increasing masses of cooled air are accumulated behind the polar front. This must continually advance, with the effect that the tracks of the corresponding cyclones are always moved farther towards the south. Finally, at the place of least resistance great masses of cold air break through and are expelled in the direction of the tropics. The polar front performs a corresponding retreat, the cyclonic tracks are again displaced toward the north, and the type of weather is changed. Then the same action repeats itself. This intermittent form of the great atmospheric circulation is especially pronounced in winter. During the summer the polar front is far back, and the high temperature of the continents exerts a considerable influence; then occasionally a continuous return of polar air may be established along the west coast of the continents, leading direct into the trade winds."

These views of Bjerknes are a valuable contribution to meteorology, but need modification in details.

Following similar lines of research, C. LeRoy Meisinger,[5] using the records from instruments lifted by kites and balloons in the United States, traces out the manner in which warm southerly winds overflowing cold winds from the north produce zones of rain, glaze, sleet and snow.

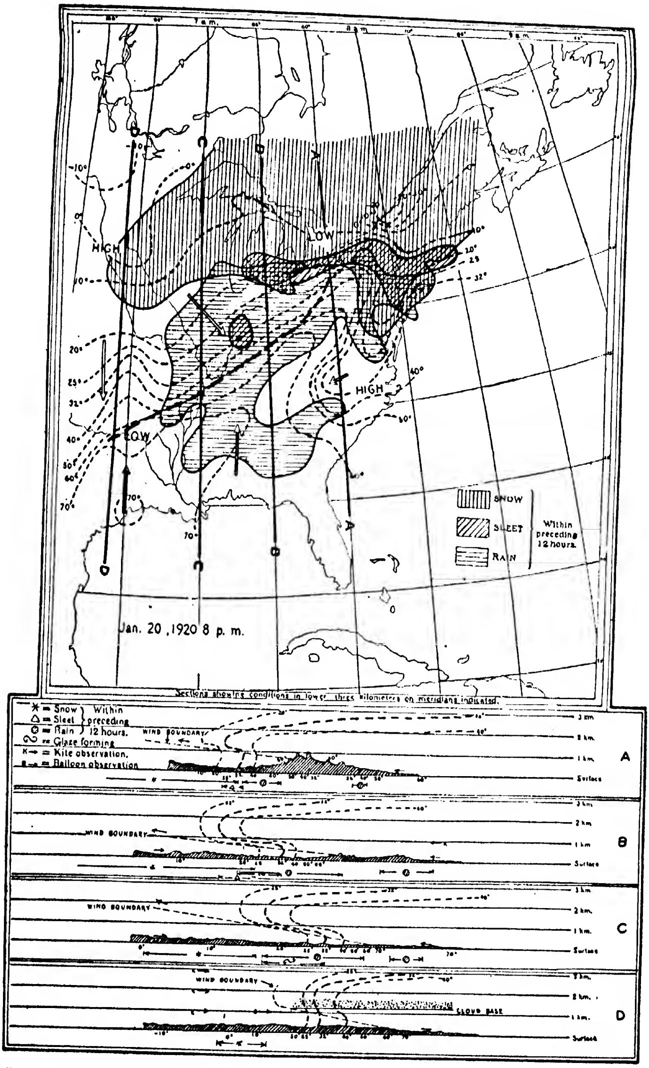
Fig. 159 gives a map of the eastern half of the United States for 8 P. M. January 20, 1920, showing the isothermal lines and the areas of snow, sleet and rain during the preceding twenty-four hours. South of the rain front, as shown on the map, there was a broad stream of warm southerly winds which overflowed a cold northerly current extending from the rain front to the northern boundary of the United States.

In the lower part of the diagram are given four vertical sections up to three kilometers along the heavy lines *AA*, *BB*, and *CC* in the chart. The broken line shows the boundary of the northerly and southerly winds and the dotted areas show the areas of cloud. The symbols used for indicating the kind of precipitation observed are explained in the side of the diagram and the method of obtaining the observation, whether by kite or balloon, is shown by *k* or *b* in the body of the diagram.

The chart shows by means of heavy arrows the general trend of the surface winds, and the vertical sections indicate how the surface wind passed upward over the northerly winds, producing

[5] Meisinger, C. LeRoy—"Preliminary Steps in the Making of Free-Air Pressure and Wind Charts," *Monthly Weather Review,* Vol. 48, No. 5, p. 7, Washington, May, 1920.

FIG. 159



Snow and Sleet Formed in Air Overflowing Cold Current from North in the United States—After Meisinger

clouds and precipitation. The direction of the winds at different levels, as shown by kites and balloons, is indicated by arrows which fly with the wind.

After the ascending stream has cooled to the condensation point, precipitation begins and the heaviest rain occurs during the first thousand meters, because the air then contains the most moisture. When the rain falls through a layer of air below the freezing point (32° F.), as indicated in section A, the rain-drops cool and freeze on touching solid objects, forming a smooth coating of ice or glaze as represented in the figure by the symbol ∾. After the ascending current of air has fallen below the temperature of 32° F., the precipitation is in the form of snow. For the formation of hard pellets of sleet, it seems that the condensation must begin at a higher level as snow, then fall through a warmer current in which the snow is partly melted or is covered with a layer of water, after which it falls into the cold surface current from the north and is frozen before reaching the ground.

For the study of problems of this nature, the diagrams of Hertz, Neuhof and Von Bezold are extremely useful. Fig. 167 is a form of the Hertz-Neuhof diagram, modified slightly from one constructed by Geddes.

In using this diagram, it is necessary to know, or be able to estimate, the slant of the ascending or descending air. It is only during the hours when the sun is well above the horizon that the earth's surface is heated enough to form currents of air rising nearly vertically and then usually only in the lower 7000 feet (2000 m.), except in the case of thunderstorms. Above the level of the daily convection currents and surface cooling at night, the cold air from the north is descending down a long slope and heating adiabatically, that is, at the rate of 1.8° F. (10° C.) for every 102 meters (340 m. ft.) of descent, while the warm moist air is ascending a long slope and cooling at the adiabatic rate of saturated air. This slope is outlined by the slope of the line separating the two systems of winds. To take an example, let it be assumed that the surface air has a temperature of 59° F. (15° C.), a pressure of 1016 mb. (30.0 in.), a vapor content of 7.1 grams per cu. m., giving a relative humidity of 70 per cent. The rising air will change condition as represented by the black line. It will first cool 18° F. (1° C.) for each 102 meters of ascent, the relative humidity will steadily increase until the saturation is reached at the dotted line of 7.1 grams at a height of about 800 meters. Up to that height the air follows the trend

of the continuous slanting lines and after that it follows the trend of the broken slanting line. At 32° F. (0° C.) the cooling will halt until all the moisture is frozen and will then follow the trend of the broken lines. The amount of moisture precipitated can be computed from the dotted line.

CHAPTER VII

MOISTURE, CLOUDS AND RAINFALL

SUMMARY

The chapter treats of the rôle of water vapor in the air. The clouds are given names and the causes of their formation discussed. The cumulus type of clouds is formed from local ascending currents while clouds forming sheets or strata are due to slow oblique ascent of moist air. The succession of clouds in a storm are given and the origin and development of local storms like thunderstorms and tornadoes are explained.

THE moisture in the air in the form of invisible water vapor plays a very important part in modifying other weather conditions, and by its absorption of solar or terrestrial heat may even become a cause of weather changes. The water vapor absorbs the heat radiation from the earth and thus protects the earth from the cold of space like a veritable blanket.

Without water vapor in the atmosphere there could be no clouds, nor rain, nor sleet, nor snow. No thunder would startle nor fogs depress us. A universal drought would prevail over the face of the earth and life would be impossible. In every current of air there is an invisible cargo of water and the billowy clouds which are seen on sunny afternoons might poetically be considered the sails of a vast argosy bearing countless tons of water to the thirsty land to supply the needs of the living world of plants and animals.

The absorption of solar and terrestrial radiation by water vapor will be a subject for later treatment.

When vapor is lifted by ascending currents, it cools by expansion, and if the cooling is sufficient the vapor is condensed into visible particles of water. Aitken has shown that condensation in particles cannot take place without a nucleus, which is generally furnished by the fine dust in the air, although it is now considered that electrons or ions may also be nuclei.

Without these nuclei supersaturation would be possible and when condensation began the water might fall in sheets, but as abundant nuclei are always present this condition has only a theoretical interest.

PLATE IV

Photo. by W. Dearden

Cirro-Stratus

PLATE V

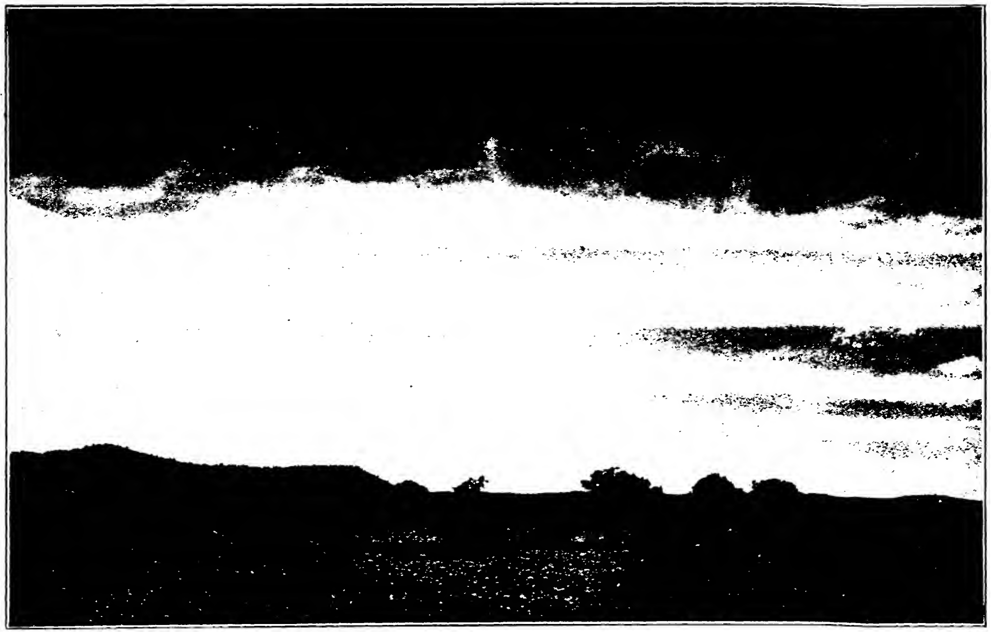


Photo. by W. Dearden

Cirro-Stratus in Bands

PLATE VI

Photo. by A. B. Murray

Cirro-cumulus in Undulations

PLATE VII

Photo. by W. Dearden

Alto-Cumulus

Photo. by T. W. Kilmer

Cumulus

PLATE IX

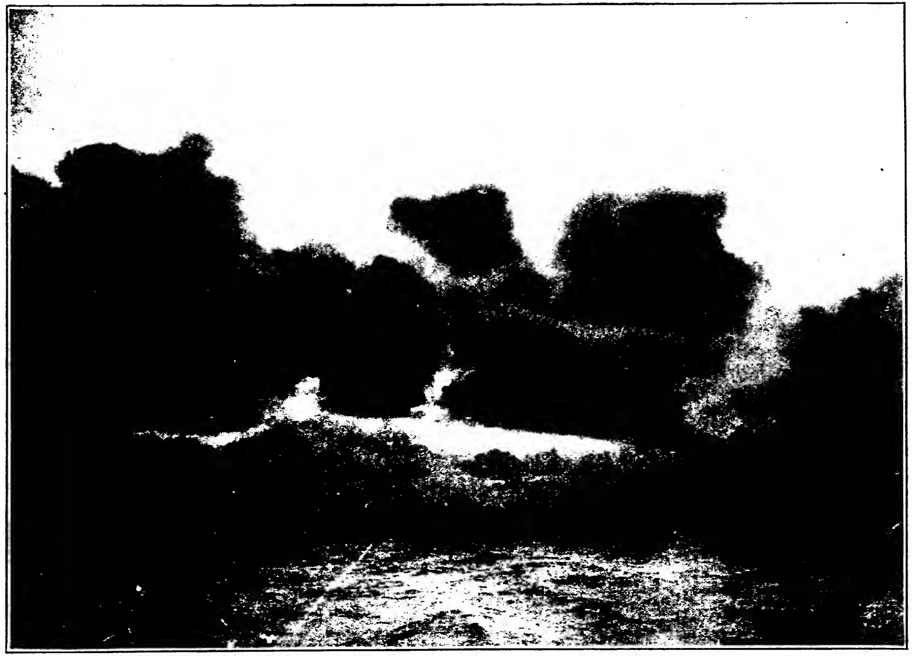


Photo. by Harry D. Williar

PLATE X

Photo by Harry D. Willis

In nature the condensation appears to begin even before the temperature of saturation is reached, and to this cause Frank Proctor attributes the haze which fills the air on certain days, especially in summer.

When the temperature of saturation is reached cloud formation begins.

CLOUDS

When the ascent of moist air is sufficiently rapid and the expansion sufficiently great the cooling condenses the moisture into masses built up of numerous small droplets, which the ancients believed to be hollow vesicles, but which are now known to be solid droplets of water. These masses of accumulated droplets assume a great variety of shapes, but Howard found that they could be classified into a few types which he called cumulus, cirrus, stratus and nimbus. Intermediate forms he called by compound names like cirro-cumulus, cumulo-stratus, etc. This system of classification was published in 1803.

In the course of time other names were added by various students of clouds, as, for example, lenticular-cumulus, turreted-cumulus, palio-cirrus, cirro-nebula, alto-cumulus, alto-stratus. There had long been a feeling that the cloud system of Howard needed extension and modification and Hildebrandsson and Abercrombie, by persistent effort, succeeded in obtaining the adoption of a modified system by the International Meteorological Congress of 1891.

The cloud names and descriptions adopted and later modified are given below.

1. *Cirrus* (Ci.)—"Detached clouds, delicate and fibrous looking, taking the form of feathers, generally of a white color."

2. *Cirro-stratus* (Ci.-St.)—"A thin, whitish sheet of cloud, at times completely covering the sky and only giving it a whitish appearance (it is then called cirro-nebula); at other times presenting more or less distinctly a fibrous structure like a tangled web."

3. *Cirro-cumulus* (Ci.-Cu.) (Mackerel sky)—"Small globular masses or white flakes without shadows, or having very slight shadows; arranged in groups and often in lines."

4. *Alto-cumulus* (A.-Cu.)—"Largish globular masses, white or grayish, partially shaded, arranged in groups or lines and often so closely packed that their edges appear confused."

5. *Alto-stratus* (A.-St.)—"A thick sheet of a gray or a bluish color," sometimes forming a compact mass of dark gray color and fibrous structure.

6. *Strato-cumulus* (St.-Cu.)—"Large globular masses or rolls of dark cloud, often covering the whole sky, especially in winter."
7. *Nimbus* (Nb.)—"A thick layer of dark clouds, without shape and with ragged edges, from which rain or snow generally falls. Through the openings in these clouds an upper layer of cirro-stratus or alto-stratus may be seen almost invariably."
8. *Cumulus* (Cu.)—"Thick cloud of which the upper surface is dome-shaped and exhibits protuberances, while the base is horizontal." Ill-defined or broken cumulus are called *fracto-cumulus.*
9. *Cumulo-nimbus* (Cu.-Nb.)—"Heavy masses of cloud rising in the form of mountains, turrets, or anvils, generally surmounted by a sheet or screen of fibrous appearance . . . and underneath a mass of cloud similar to nimbus." Broken fragments of nimbus or "scud" are called *fracto-nimbus.*
10. *Stratus* (St.)—"A horizontal sheet of lifted fog," or a sheet of foglike cloud at a low level, but not resting on the ground. Ragged, ill-defined fragments, or lifted fog in isolated masses are called *fracto-stratus.*

In addition to the ten types described above certain especial types are described.

Lenticular cloud bands—Banks of clouds of an almond or airship shape, with sharp general outlines, but showing on close examination, fretted edges, formed of an ordered structure of cloudlets similar to alto-cumulus or cirro-cumulus, which is also seen in the bank itself when the illumination is favorable.

Mammato-cumulus—Clouds which show a mammated or udderlike under surface. These are usually the result of descending cloud masses.

Arranged in a systematic scheme as regards height and condition of occurrence the system is as follows:

a. Detached or rounded forms (chiefly in dry weather).
b. Widespread or veil like forms (rainy weather).

A. Highest clouds, averaging 9000 meters (30,000 ft.).
   1. Featherlike clouds (cirrus).
   2. Thin sheets (cirro-stratus).
B. Middle clouds, 4000 to 6500 meters (13,000 to 22,000 ft.).
   3. Small balls, glistening white (cirro-cumulus).
   4. Large balls, as of white cotton (alto-cumulus).
   5. Thick ashy or blue-gray sheets (alto-stratus).
C. Low clouds, 1500–2000 meters (5000 to 10,000 ft.).
   6. Large balls or rolls of gray cloud masses (strato-cumulus).
   7. Torn sheets of gray clouds, from which rain usually falls (nimbus).

D. Clouds of the ascending currents, 1500–5000 meters.
   8. Piled clouds (cumulus).
   9. Thunder-shower clouds (cumulo-nimbus).
E. Elevated fog (stratus) under 1000 meters.

Up to the present all systems of cloud nomenclature have been based on the forms of clouds coupled with the heights or conditions in which they occurred. Any further advance must be made by associating the forms with their physical causes and methods of development.

CAUSES OF CLOUD FORMATION

There are undoubtedly in the air three primary causes of cloud formation: (1) The ascent of moist air in local, nearly vertical, ascending currents caused by an adiabatic lapse rate in the air. In dry air this rate is 1.8° F. in 340 feet (1° C. in 102 m.) and in saturated air somewhat less. (2) The ascent of moist, saturated air in ascending currents inclined upward at a slight angle. This type of cloud is caused by the overflowing of cold air by warmer air or the ascent of air up the slopes of mountains as the result of the prevailing wind system. (3) The chilling of moist air by radiation either from the air itself to space or by radiation to the earth, which is frequently colder than the air above it. (4) The mixing of air currents at different temperatures when the warm current is nearly saturated with moisture. Clouds caused solely in this latter way are rare. Mixing is usually a modifying condition and is accompanied by waves at the top of the cold current analogous to ocean waves.

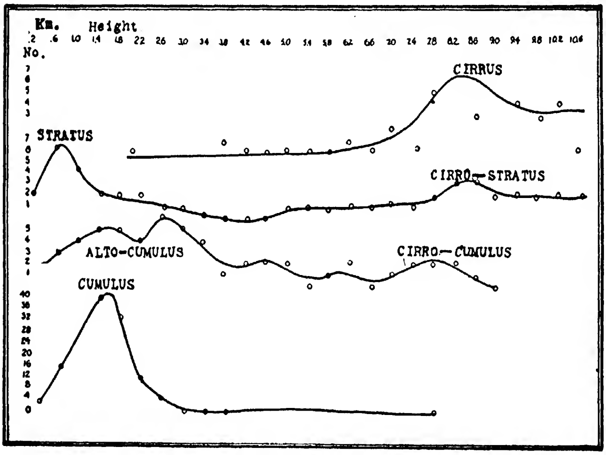
The ascent of moist air in local convection currents takes place chiefly at two levels, first, in the lower levels of the atmosphere, generally below 10,000 feet (3000 m.), due to the heating of the earth's surface during the day by direct insolation; and, second, in the level immediately below the base of the stratosphere where vertical instability is caused by currents with a component of motion from the equator underrunning cold air at a higher level. At high levels there is a component of motion of the atmosphere toward the equator carrying the cold polar currents over warm air below, usually air with a component of motion from the equator toward the pole, so that both factors combine to produce vertical instability.

Measurements of cloud heights in America and Europe show that there are two maxima of cloud frequency in the air, one is

between 500 and 2000 meters (1500 to 7000 ft.) and the other at the height of about 8 to 9 kilometers (5 to 5.5 mi.). See Fig. 160.

The isolated cumulus and the isolated cirrus are really clouds of the same nature caused by local ascending convection currents, but at different levels and at different temperatures. When cumulus are formed at a very low temperature there are frequently seen long fibers streaming behind, due to falling snowflakes, and the upper part evaporates slowly and is drawn out into cirruslike bands. Ordinarily the light particles of rain fall-

FIG. 160



Frequency of Clouds at Different Heights

ing from the base of the cumulus are quickly evaporated, but in arid regions streaks of rain which do not reach the earth's surface are seen falling from large cumulus clouds forming cirruslike fibers, but of a dark color. That the long fibers which stream downward and backward from tufts of cirrus are really snowflakes has been proved by Berson and other aëronauts who have intercepted them when ascending to great heights. The slow evaporation of the cirrus also permits it to be drawn out into long bands, by wind currents of different velocities; while the top of the cumulus, when carried beyond the local ascending current, quickly evaporates. The slow evaporation of the cirrus is due to the extremely low temperature in which it is formed,

some sixty to seventy degrees below zero Fahrenheit (about −65° C.).

The formation of widespread sheets of cloud by currents of warm air ascending an incline over bodies of cold air is illustrated in Figs. 154 and 157. This is the class of cloud which beginning as nimbus or stratus at low levels changes to alto-stratus and cirro-stratus at higher levels. The alto-cumulus and cirro-cumulus are developed in place of alto-stratus or cirro-stratus when the ascending currents are weak. The forms of these clouds are largely determined by wave movement which always exists when a current of warm air flows over colder air masses. The atmospheric waves cause these clouds to break up into long bars or ripples like those made in the sand by rippling water (see Plate VI). Clouds of this class as well as alto-stratus and cirro-stratus are found in the colder stratum immediately beneath a stratum of warmer air and not in the warmer stratum immediately above a stratum of colder air as the theory of Bjerknes might lead one to believe and shows that his theory will need some modification to fit it to the known facts. Also small cumuluslike clouds normally are not formed immediately above a colder current by the lifting of the air by the colder current as represented in Fig. 156; but, if found at all, are usually at the top of the cold current due to ascent of air from the earth's surface or from a warmer stratum below the cloud. A special study of cloud formation above Blue Hill Observatory, near Boston, was made from data obtained with kites. The kites were attached successively to a steel wire which at times was unreeled to a length of several miles and sustained by six or more kites in tandem. To the upper kite was attached an instrument recording temperature, pressure, humidity and wind velocity and at times a second instrument of the same class was attached to a kite at a lower level.

The upper kite was followed by an observer with a theodolite and readings of the angular altitudes of the kite were taken from moment to moment. With this reading and a simultaneous record of the length of flying line out to the kites, its height above the earth's surface could be calculated. When any kite or line entered or emerged from a cloud stratum, its angular altitude was taken and its height determined. In this way a number of measurements of the height of a cloud stratum was frequently obtained during a kite-flight.

The measurements of the heights of cumulus clouds clearly proved that they are due to condensation of moisture rising from

the surface of the earth. The temperature decreased at the adiabatic rate, that is at the rate of cooling air freely expanding without the addition of heat.

This rate is 0.53° F. per 100 feet or 0.98° C. per 100 meters. The relative humidity steadily increases as the air cools and when the point of saturation is reached at the calculated height (see Fig. 167) cloud formation begins.

Knowing the amount of moisture in the air it is easy to compute the height at which cloud formation will begin. From observation at the ground the dew point, or temperature of condensation, can be determined. On account of the larger volume occupied by expanding air the dew point is lowered 0.20° C. for each one hundred meters of ascent and this must be deducted from the adiabatic rate. Hence $0.98° - 0.20° = 0.78°$ C. which divided into the difference between the air temperature and the dew point, ought to give approximately the altitude in hectometers where the air is cooled to the dew point and condensation into cloud begins. If the readings are in Fahrenheit degrees, dividing by .0042 will give approximately the height in feet. This easy method of finding the height of the lower clouds may prove of importance in aeronautics.

How well this worked out is shown by the following observations of the base of cumulus clouds at successively higher levels as observed at Blue Hill.

TABLE XI

Date	*Height Observed Meters*	*Height Computed Meters*	*Date*	*Height Observed Meters*	*Height Computed Meters*
Sept. 23, 1898...	531	586	June 21, 1899...	1,684	1,680
July 17, 1906...	850	808	Mar. 7, 1901...	1,766	1,801
June 15, 1908...	1,064	1,052	June 22, 1900...	2,051	2,037
July 16, 1904...	1,248	1,352	May 1, 1900...	2,793	2,660
Nov. 7, 1898...	1,403	1,445	May 5, 1904...	2,830	2,825

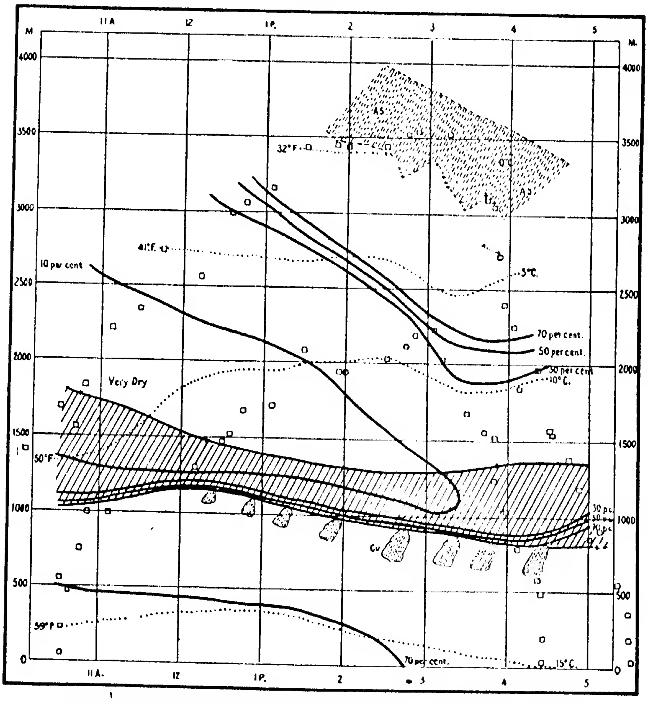
These results are entirely in accord with the view originally set forth by Espy. Turbulence and mixture cause the heights to exceed the computed heights at times and should be taken into account if greater accuracy is desired.

Clouds of the type of cumulus where the bases are joined and the tops appear like the turrets of a tower, called by Ley "turreted cumulus," were found to occur when a warm current at some distance above the earth's surface came in beneath a colder current at a higher level and caused an adiabatic gradient in the

air above one thousand meters, while below one thousand meters the temperature was less than that of the air immediately above it.

Clouds which form in sheets such as nimbus, stratus, alto-stratus and cirro-stratus are generally inclined to the horizon, indicating that they are caused by moist air ascending in strata directed obliquely upward.

Fig. 161



Inclined Cloud Strata in Advance of Storm, Blue Hill, Sept. 20, 1900

Fig. 161 taken from the *Annals of the Harvard College*, Vol. 48, Part 2, p. 179, Cambridge, 1911, gives a plot of the observations made on September 20, 1900, when an area of rain was approaching. On that day two kites on the flying line carried meteorographs, one at the top of the line and a second 2500 meters (8300 ft.) from the top. The hours of the day are

given at the top of the vertical lines while the horizontal lines show the heights in meters. Places where the kites entered clouds and inverted gradients of temperature are shown by small crosses. Small squares show the positions of the meteorographs at short intervals. Lines of equal relative humidity are drawn for each 20 per cent from 10 to 70 per cent and saturation, or approximate saturation, is indicated by the position of the clouds. The clouds are indicated by broken lines and an inverted gradient of temperature (within which the temperature rose with increase of height) is indicated by an area shaded with straight lines. At 1.52 P. M. the upper kite entered a sheet of alto-stratus at a height of 3474 meters. Successive measurements showed that the base of this cloud varied in height in a wavelike manner, indicating undulation in the height of the cloud; but on the whole the base became progressively lower, as is shown by the diagram, indicating a decided inclination of the cloud stratum and, hence, an ascensional movement of the air within the cloud.

The upper surface of the cloud was not reached, but its probable position is shown by the broken line. This case is typical of all the cases where a number of successive measurements were made. In no case was the cloud stratum found to remain at a constant height for any long interval.

Fig. 162 shows an inclined stratum of cloud in the rear of a storm. It changed from alto-stratus to alto-cumulus as it increased in height and grew gradually thinner, disappearing entirely at 2.10 P. M. At a lower level a stratum of strato-cumulus was formed also tilted upward, indicating an oblique ascent. This cloud is caused in part by ascending convection currents like those which form cumulus, so that it really is what its name implies, a combination of the stratus and cumulus types of cloud formation.

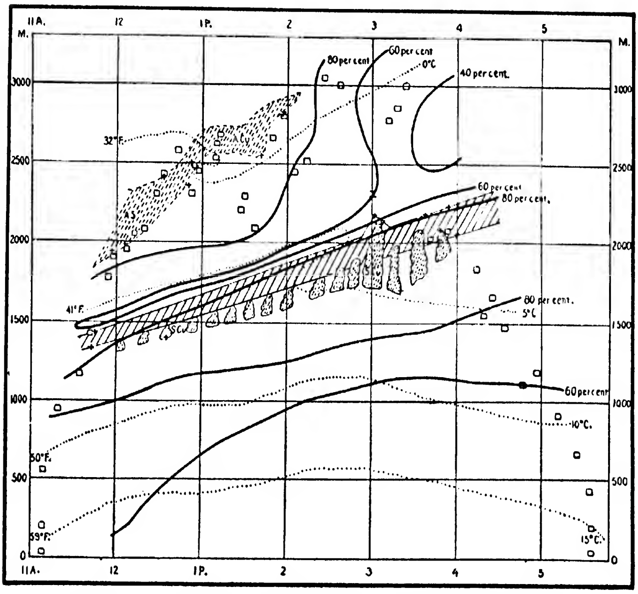
It will be noticed that the tilting of the strata is in opposite directions on the opposite sides (east and west) of the storm.

One of the most interesting facts in connection with cloud formation is that all clouds are closely connected with inverted lapse rates or inverted vertical gradients of temperature (regions in the atmosphere where the temperature ceases to fall and for a short distance upward rises with increasing height). The top of the cloud is usually in the coldest air immediately beneath the inverted vertical gradient of temperature. This fact is shown in all the diagrams, the clouds in each case being found immediately beneath the inverted vertical gradient. The question arises as to whether these inversions are caused by the

clouds. But the fact that they exist in cloudless skies before the formation of clouds and the fact that they exist at night as well marked as by day prove that clouds and radiation from clouds are not necessary for their formation.

These inverted gradients of temperature exist at all times in the air, but they are much modified by ascending and de-

Fig. 162



Inclined Cloud Strata in Rear of Storm, Blue Hill, Sept. 18, 1900

scending currents of air and are no doubt in many cases caused by them.

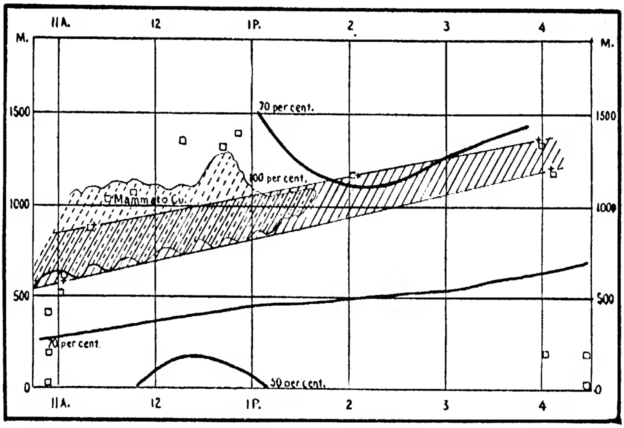
Another interesting fact is that the tops of the cumulus clouds, on account of the inertia of the ascending currents, frequently enter into the warmer currents above, so that the tops of the clouds are much cooler than the air surrounding them.

Only infrequently are clouds found in the base of a warm current above a cold dry current and in that case the base of the cloud often sinks down in folds and protuberances, the heavier portions of the cloud falling faster than the lighter portions and

forming clouds of the kind which have been named mammato-cumulus. Fig. 163 gives an example of such a case observed at Blue Hill on July 22, 1898. Turbulence may also be a factor.

The fact that the cloud is usually formed at the top of an obliquely ascending current of air and not at the base along the oblique slope forming the plane of separation between the warmer and colder air, as Bjerknes' theory would lead one to suppose, is a condition which needs explanation. There is a marked in-

FIG. 163



Conditions of Formation of Mammato-cumulus, Blue Hill, July 22, 1898

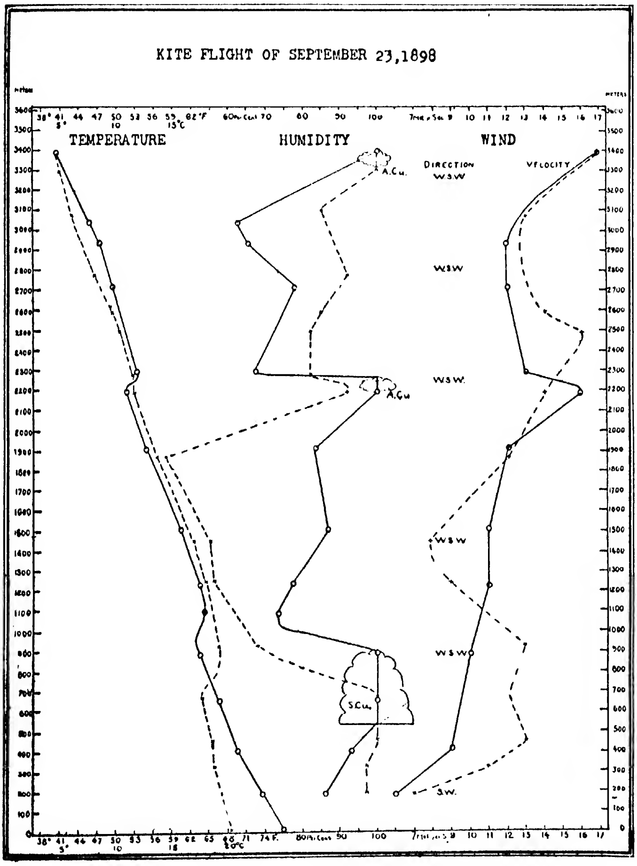
crease of wind velocity near the level of the cloud and a diminished velocity intermediate between the cloud strata.

This fact is clearly shown in Fig. 164, taken from Bulletin No. 1, 1899, of the Blue Hill Meteorological Observatory. It is possible that the increased velocity of this current acted on by the part of the deflective force directed away from the axis of the earth's rotation in winds from the west is the additional force necessary to carry the cloud stratum from the plane of meeting between the cold and warm air currents to the height of the inverted vertical gradient of temperature at the top of the warmer current, separating it from a potentially warmer current above. By "potentially warmer" is meant that it would be warmer if reduced to the same level and heated by compression in descent.

The thickness of a cloud stratum in any given case may be

determined by measuring the altitude of the cloud when entered by the kite and next determining the altitude of the top of the cloud by the sudden fall of humidity which occurs when the

FIG. 164



Plot of Weather Conditions in a Vertical Section Over Blue Hill, Mass.

meteorograph rises above the top of the cloud. The number of cases observed at Blue Hill was not great, but the results are interesting and are given below:

TABLE XII

THICKNESS OF CLOUDS

Kind	Cases	Mean Height Meters	Thickness in Meters		
			Mean	Max.	Min.
Alto-Cumulus	2	2,497	59	98	20
Alto-Stratus	8	2,263	207	344	30
Cumulus	8	1,380	479	766	225
Fracto-Cumulus	3	937	91	168	25
Strato-Cumulus	12	1,084	235	618	97
Stratus	6	713	240	380	210
Nimbus	13	704	891	2,545	100
Fracto-Nimbus	2	682	117	150	85

Next to the nimbus, the cumulus is the thickest cloud measured and fracto-cumulus and fracto-nimbus are both thin clouds, as was to be expected. The thickest of all clouds is the cumulo-nimbus, which sometimes reaches a vertical height of several miles, as shown by theodolite measurements.

The height at which cloud formation can take place in the lower air is determined by the height above sea level of the lowest inverted gradient of temperature. If this inverted gradient is at so low a level that ascending bodies of air from the earth's surface do not cool to the temperature of the dew point before reaching it, then no clouds are formed because further ascent is checked in these bodies of ascending air as if by an impenetrable screen. Hence, the height above sea level of the lowest, inverted vertical gradient of temperature and the difference between the air temperature and the dew point determine whether a day shall be cloudless or partly cloudy. On a cloudless day, if the dew point increases, a condition may arise in which ascending bodies of air are cooled so that saturation is reached and cloud formation begins before the rising air reaches the inverted vertical gradient of temperature. In such cases cloud formation will begin suddenly, and frequently the clouds will cover the whole sky.

On cloudless days, cloud formation may also be brought about by a rise in temperature, so that ascending bodies of air, cooling adiabatically, do not cool so much as to be colder than the air at the level of the inverted vertical gradient of temperature when they reach that level. In such cases the inverted gradient suddenly disappears and the ascending current continues on upward until cloud formation begins. Thus, in Fig. 164, if the temperature of the air at the ground had been 80° F. instead of

77° F. the air would not have been colder than the air above it when it reached 1000 meters and would have continued upward to about 2000 meters.

Three years of hourly cloud observations at Blue Hill showed that the most frequent succession of cloud forms preceding rain was first cirrus, which gradually thickened into cirro-stratus and later became alto-stratus and finally developed into nimbus with rain. Or else the order was first cirrus, then cirro-cumulus and cirro-stratus, alternating, followed by alto-cumulus or alto-stratus and then nimbus.

When only one stratum of cloud was observed the first order of sequence occurred in 47 per cent of the cases and the second in 38 per cent of the cases or a total of 85 per cent, the remainder being cases where cirro-cumulus or some lower cloud form was the first to appear.

In many cases, however, there was more than one stratum of cloud preceding rain. Out of 132 observed cases there was one stratum in 50 per cent of the cases, two strata in 35 per cent of the cases, three strata in 11 per cent, and four strata in 4 per cent.

When there were more than two strata, the highest usually began with cirrus or cirro-stratus, the second with cirro-cumulus or alto-cumulus and the lower with some lower cloud form like strato-cumulus which gradually thickened into nimbus.

In the rear of the rain, in 37 per cent of the cases there was one stratum of cloud, in 51 per cent two strata, in 10 per cent three strata and 2 per cent four strata. The most frequent order of succession of clouds in the higher strata was alto-stratus, thinning out to cirro-cumulus, cirro-stratus or cirrus; and in the lower strata was strato-cumulus clouds decreasing in amount, as illustrated in Fig. 162. The strato-cumulus in these cases arises from adiabatic temperature gradients in the lower air, the cloud partaking of the nature of ordinary cumulus, whose formation has been previously explained.

Preceding the formation of thunderstorms the most frequent clouds observed were cirro-cumulus and alto-cumulus and especially if the alto-cumulus took the form of turreted-cumulus, which, as previously shown, indicate adiabatic temperature gradients at a high altitude. Cirrus clouds as a rule move with the general atmospheric drift from west to east, but there is a very interesting difference in the form of the cirrus clouds which appears in advance of the rain from those which follow it. In advance of the rain the fibers or snowflakes which trail down-

ward from the thicker part of the cloud extend backward toward the west in the form of long trailing fibers resulting from the fact that the cloud stratum is moving faster than the air below it; while in the case of the cirrus clouds in the rear of the storm the trailing fibers are in advance of the main body of the cloud that is on the eastern side because the cloud stratum is moving against the general drift of the atmosphere and hence moving less rapidly from the west than the air below it.

On the average, the cirrus first appears about 26 hours before rain, cirro-cumulus about 21 hours, cirro-stratus about 13 hours, alto-cumulus about 8 hours and alto-stratus about 6 hours.

The probability of rain following within twenty-four hours after the first appearance of each cloud increases as the cloud stratum reaches a lower level. At Blue Hill it was as follows:

TABLE XIII

FREQUENCY OF CLOUDS BEFORE RAIN

Kind of Cloud	*C.*	*Ci-St.*	*Ci-Cu.*	*A-Cu.*	*A.S.*
Frequency of rain within 24 hours......	33%	36	44	45	68

After the appearance of alto-stratus rain followed 68 per cent of the time. In many cases of cloud formation, however, the rain stage is not reached and the cloud passes away without rain falling.

THE THUNDERSTORM

Undoubtedly one of the most awe-inspiring occurrences in cloud-land is the thunderstorm and its associated phenomena, the clouds which tower to enormous heights, the blinding lightning and rolling thunder, the torrential rain or pelting hail, and the destructive squall.

The ancient Roman saw in the thunderstorm the mighty power of Jove in his majestic anger hurling thunderbolts at his offenders, and the Goths heard the terrific reverberating blows of Thor forging on his anvil the armor for the gods.

The thunderstorm is of a complex nature. The cloud is anvil-shaped, as shown by the accompanying sketch, Fig. 165.

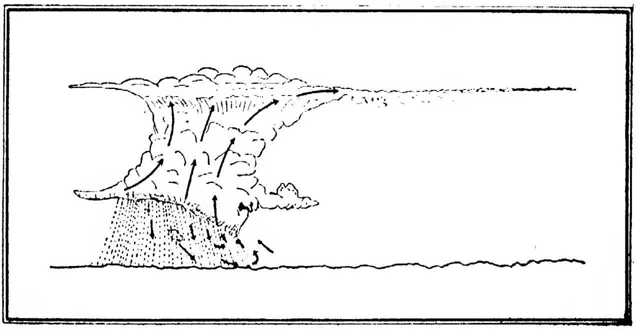
In front of the cloud and within the cloud there is a strong ascent of air, while beneath the cloud is a torrential rain and an outrushing squall, the result, (1) of the downward drag of the air by the rain drops, (2) of the chilling of the air by the

rain, and (3) sometimes of the incoming of cool air in the rear of the storm, as illustrated in Fig. 156.

In the inclined plane separating the ascending air and the outrushing squall there is developed a dark roll of cloud turning on a horizontal axis which adds much to its terrifying effect. These various features are illustrated by the outlines sketched in Fig. 165.

The outlines in Fig. 165 are intended to give a cross-section of a thunderstorm to illustrate the various changes occurring in different parts of the storm. Beneath the thunder cloud is a descending current of air and there is a heavy fall of rain. Some-

FIG. 165



Sketch of Thundercloud

times fragments of cloud can be seen descending with the rain. In front of the rain is a low-hanging roll of cloud between the descending air under the cloud and a strong ascending current in front which is inclined upward and feeds the cloud. Within the cloud there is a rapidly ascending current of air which takes on a whirling motion when the updraft is rapid. At the top of the cloud the air blows outward forming the anvil-shaped top at a great height (3 miles or more). The outflow is strongest in front in the direction of drift of the cloud and suspended from the tops can frequently be seen rolls of descending cloud matter forming mammato-cumulus.

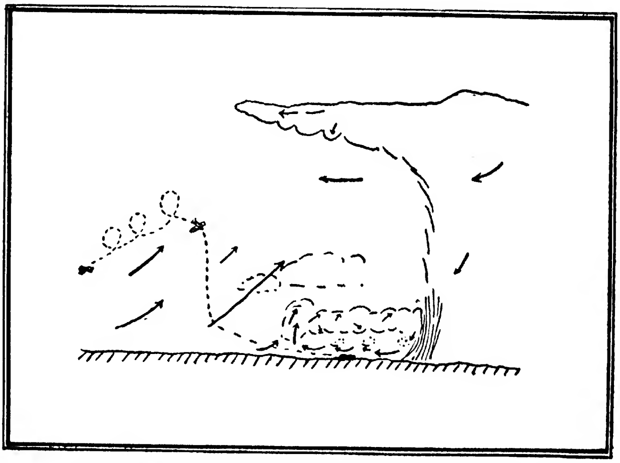
Fig. 166 gives a sketch of the front of a thunder cloud (cumulo-nimbus) drawn from a description of Lieutenant Cobb by C. F. Brooks.[1] Lieutenant Cobb was stunting near Love Field, Texas,

[1] Brooks, C. F.—*Monthly Weather Review*, Vol. 47, p. 531, Washington, Aug., 1919.

at about 3500 feet altitude during the approach of a thunderstorm. After doing three evolutions, taking about fifteen minutes, he found that he had gained some 3500 feet (1100 m.) in altitude, instead of losing 1500 feet (500 m.) as was usual. Sometimes the lifting would be of the order of 500 feet in a minute.

This indicates that there was a wind with an average vertical component upward at about 5 miles per hour (2 m. per second) blowing toward the storm. At the end, the aviator noticed sharp mammato-cumulus above, and strato-cumulus clouds

FIG. 166



Sketch of Front of Thunderstorm as Seen from Airplane

below him. He seemed to be at an altitude about midway between them, though he was some 5 miles (8 km.) away from the storm front. On descending, he entered extremely bumpy air and was able to land only by driving into the wind with the engine on. For course of flight see looped curve with broken lines in Fig. 166.

On another occasion Lieutenant Morgan, while flying in front of a thunderstorm, was suddenly lifted from 2000 to 7000 feet (700 to 2300 m.).

The American aëronaut Wise once made an ascent in front of a thunderstorm and was drawn by an ascending current into the thunder cloud. When in the cloud, he was caught in a whirl

and spun around in a circle with frightful rapidity. The air was intensely cold, so that his beard, his clothes and the rigging of the balloon were soon encased in ice. He was pelted by driving rain, mingled with hail and snow, and in the meantime his balloon was drawn steadily upward to the top of the cloud, where it was thrown outward into the clear air. At a short distance from the cloud it began to descend rapidly and he expected soon to be safe on the firm earth after his thrilling experience; but when near the base of the cloud he was again drawn into the cloud and again passed through the terrible maelstrom to the top of the cloud, but now, with all his ballast and most of his gas gone, he came down with such rapidity that he passed through the indrawing stream of air and reached the ground in safety, his balloon-cover acting as a parachute.

This experience of Wise suggests the method of hail formation. The drops of water carried to the top of the cloud by the swift ascending current are frozen by the intense cold, and, passing out of the ascending current at the top of the cloud, fall to the base of the cloud, where they are once more drawn into the whirl, there covered with water and ice and carried to the top of the cloud from whence it again falls. This process may be repeated until the hailstone is too heavy to be lifted by the ascending current, when it would fall to the ground. In this way the various concentric coats of the hailstone are explained. When the whirl in the thunderstorm becomes exceptionally strong it extends downward below the base of the cloud, develops a funnel and becomes the fearful tornado or waterspout.

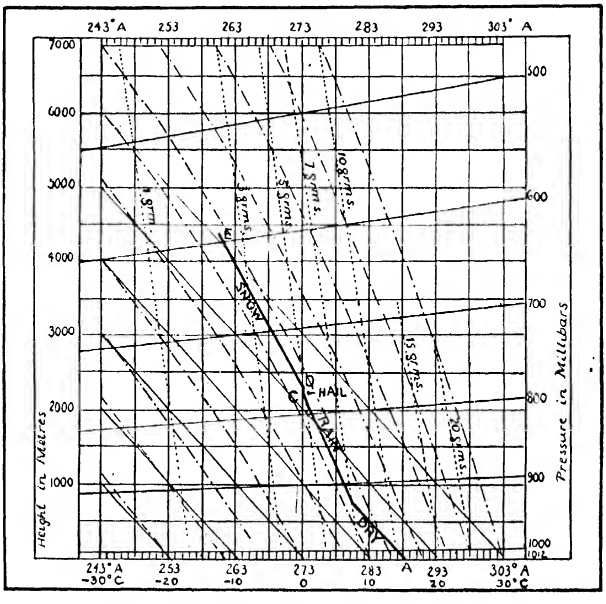
Thunderstorms can be divided into two classes, (1) the isolated shower and (2) the line squall. The isolated shower develops from the ordinary cumulus cloud, which becomes more intense than usual by the extension of the adiabatic gradient to a great height. The whole process has been followed by means of observations with balloons and kites. An example is given in the *Annals of the Astronomical Observatory of Harvard College*, Vol. 48, Part 2, p. 186. In such cases there is a decrease of temperature at the adiabatic rate of dry air, 1.5° F. per 300 feet (0.98° C. per 100 m.) up to the base of the cloud and after that a decrease at the rate of saturated air. The whole can be followed by means of the diagram Fig. 167.

The steep, vertical gradient of temperature which causes the local thunderstorm may be brought about by unusual heating of a land surface over which there is a stratum of moist air, or it may arise from an inflow of equatorial winds under a prevailing upper

wind from the west. They usually occur in the afternoon, when the land surfaces are most heated, and may occur day after day in summer near the same spot.

Brooks [2] believes that the local thundershower has a tendency to grow outward at the edges and decrease in energy at the center

Fig. 167



Neuhoff-Hertz Diagram

until a cleared space is formed surrounded by a ring of cloud. He says:

"Local thunderstorms tend to originate most often where large volumes of moist air readily warmed are forced upward, e.g., broad expanses of meadow land or river flats and over cities, hills and mountains. . . . Within a homogeneous area, however, the wetting of strips by local showers temporarily makes the dry strips the loci of thunderstorm formation. At College Station, Texas, during a rainy week in the latter part of August, 1918,

[2] Brooks, C. F.—*Monthly Weather Review*, Vol. 50, p. 283, Washington, June, 1922.

this phenomenon was noted very clearly, and local forecasts of thunderstorm rains were successfully based on the width and position of strips wet by thunderstorms on the preceding day. . . . Any area that escapes on the first day or two heats more readily than the surrounding wet areas, and so becomes the center of greatest expansion and inflow from the surroundings and in consequence is wet by the resulting shower."

The thunderstorms accompanying the line squall are strung out along a long line, sometimes two or three hundred miles in length and usually occur within the area of the cyclone, either at the line of meeting of the cold winds in the rear of the cyclone and the warmer winds in front or else in connection with a V-shaped secondary depression (area of low pressure). These have been extensively studied in Europe by Durand-Gréville, and fine examples have been given in the United States by Hinrichs, Davis, and others. The squall-thunderstorm usually travels broadside on from some point between southwest and northwest with a velocity greater than that of the cyclone in which it forms, sometimes nearly twice as great. As the squall approaches any point, the pressure falls slowly, reaching its lowest point when the squall begins, therewith a sudden rise occurs followed afterward by a slower rise.

Simpson [3] made a study of the electricity of the thunderstorm and has furnished what appears to be a very satisfactory explanation of its origin, an account of which is here given, condensed from a summary by Humphreys in "Physics of the Air."

From the existence of hail it is inferred that an updraft of at least 8 meters (27 ft.) per second must often occur within the body of the thunderstorm since, as experiment shows, air of normal density must have approximately this upward velocity to support the larger drops, those of four millimeters or more in diameter, and because of its greater weight, even a stronger updraft to support the average hailstone.

Experiment also shows that raindrops of whatever size cannot fall through air of normal density whose upward velocity is greater than about 8 meters per second, nor themselves fall with greater velocity through still air; that drops large enough, 0.18 inch (4.5 mm.) in diameter and up, if kept intact to attain, through the action of gravity, a greater velocity than 8 meters (27 ft.) per second with reference to the air, whether still or in motion, are so blown to pieces that the increased ratio of sup-

[3] Simpson, G. C.—*Memoirs, Indian Meteor. Dept.*, Vol. 20, pt. 8, Simla, 1910; *Phil. Mag.*, Vol. 30, p. 1, London, 1915.

porting area to total mass causes the resulting spray to be carried aloft or, at least, left behind, together with, of course, all original small drops. Above sea level this limiting velocity is greater. It increases practically in the same ratio that the square root of the density decreases. Thus, at an elevation of two miles (3 km.) above sea level, where the barometric pressure is about 693 millibars and the temperature, say 59° F. (15° C.) lower than at the surface, the limiting velocity is approximately 9.4 meters (31 ft.) per second, instead of eight meters (27 ft.) the value for normal density and pressure (1013 mb.).

Clearly, then, the updrafts in thunder clouds (cumulo-nimbus) break up the drops which have grown beyond the critical size, and thereby produce electrical separation within the cloud, the larger drops as shown by Lenard's [4] experiments becoming positively charged and the smaller negatively charged. The turmoil in the cloud compels mechanical contact between the drops, whereupon the disruptive equalization of their electrical potential breaks down their surface tensions and insures coalescence. These larger drops will again be broken into fragments by the ascending currents; hence, once started, the electricity of a thunderstorm rapidly grows to a considerable maximum. After a time the larger drops reach a place where the updraft is small and fall as positively charged rain. The negative electrons, in the meantime, are carried up into the higher portions of the cumulus, where they unite with the cloud particles and thereby facilitate their coalescence into negatively charged drops. Hence the heavy rain of the thunderstorm is positively charged and the light rain negatively charged. The separation of the electricities is further explained by Harold King as a result of the arrangement of the electrons in molecules of water which is of such a nature that when a drop of water breaks into two of different sizes the smaller drop carries off an excess of negative electrons.

Another factor which probably intensifies the electricity is that when the small drops having the same kind of electricity coalesce into larger drops, the electric tension increases. Thus eight small drops have a much greater surface than a large drop into which they coalesce, because mass is proportional to the cube of the radius and surface is proportional to the square. Since electricity is a surface phenomenon, the electric density and tension increase in proportion to decreased surface. There is experimental evidence to indicate that the electrical condition of the cloud particles determines whether they continue as sepa-

[4] Lenard, P.—*Meteor. Zeitschrift*, Vol. 21, p. 249, Berlin, 1904.

rate particles or whether they condense into larger globules and fall to the earth. It is even claimed that by dropping particles of opposite electric charge into clouds and fogs they may be precipitated and dissipated. If so, negatively charged rain falling from the upper part of a cumulo-nimbus into positively charged cloud below would cause an increased precipitation.

Lightning is caused by the disruptive discharge which takes place between the oppositely electrified portions of the cloud, and thunder probably results from the sudden expansion of the air electrified and heated by the bolt of lightning.

The reason why lightning and thunder rarely occur except in connection with showers of rain and cumulo-nimbus clouds is obvious from the preceding explanation. The occasional lightning in connection with snowstorms, dust storms and volcanic eruptions may in each case be due to the fact that the collision of solid particles produces electricity.[5]

The hailstorm, the water-spout and the tornado are the extreme development of the local storm to the point of severity where they become destructive and dangerous.

The whirl of air in the midst of a hailstorm or severe local thunderstorm may develop such intensity that the whirl extends itself downward into the air below the cloud, in which case the air is so rarefied near the central core that the water vapor in the air approaching the center is condensed by expansion and forms a spout or trunk more or less cone-shaped, smaller below and larger above. In the tornado the whirl becomes so terrific that the air is rarefied almost to a vacuum at the center, and one of the most interesting phenomena observed on the passage of a tornado is the evidences of sudden explosions near the central track. Houses in which the windows and doors are closed are blown asunder by the confined air within the house when the pressure is suddenly removed in the center of the whirl. Stoppers are blown from bottles and feathers are blown from fowls so that they become almost naked. The wind also in this whirl of death reaches terrific velocities, so that the spans of iron bridges have been lifted, locomotives dragged from the track, stone houses and immense trees overturned and people tossed about as if they were feathers. But the calculations of Bigelow based on measurements made in a water-spout at New Bedford indicate that the whole of the phenomenon can be explained from thermodynamic laws in which the equilibrium of the air has

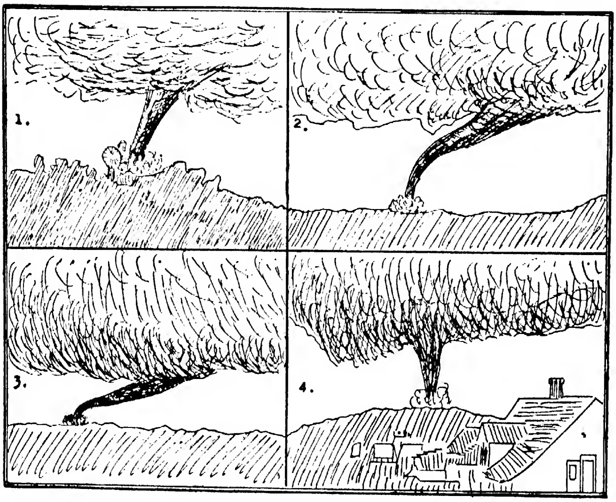
[5] Rudge, W. A. D.—*Proc. Roy. Soc. A.*, Vol. 90, p. 256, London, 1914.

been rendered unstable by a steep vertical gradient of temperature.

In writing of the tornadoes of the United States, Professor R. De C. Ward [6] says:

"Briefly stated, a tornado is a very intense, progressive whirl, of small diameter, with inflowing winds which increase tremendously in velocity as they near the center, developing there a counter-clockwise vorticular ascensional movement whose vio-

FIG. 168



Sketch of Tornado Spout Suggesting Cause of Breaks in the Whirl

lence exceeds that of any other known storm. From the violently agitated main cloud mass above, there usually hangs a writhing funnel-shaped cloud, swinging to and fro, rising and descending, the dreaded sign of the tornado. With a frightful roar as of 10,000 freight trains, comes the whirl, out of the dark, angry, often lurid west or southwest, advancing almost always towards the northeast with the speed of a fast train (20 to 40 miles an hour or more); its wind velocities exceeding 100, 200 and probably sometimes 300 or more miles an hour; its path of destruction usually less than a quarter of a mile wide, its total life a matter of perhaps an hour or so. It is as ephemeral as it is

[6] Ward, Robert De C.—*Quarterly Journ. of the Royal Meteor. Soc.*, Vol. 43, p. 317, London, 1917.

intense. In semi-darkness accompanied or closely followed by heavy rain, usually with lightning and thunder, and perhaps hail, the tornado does its terrible work. Almost in an instant it is over. The hopeless wreck of human buildings, the dead and the injured, lie on the ground in a wild tangle of confusion. . . . It is one of the most remarkable things about a tornado that even a very short distance, perhaps only a few yards, from the area of complete destruction close to the vortex, even the light objects may be wholly undisturbed."

Every student of tornadoes notices this pulsating variation in intensity of tornadoes. Photographs suggest that it is due to the breaking of the whirl by the retardation of the lowest part at the earth's surface and its re-formation something like that shown in sketches 1, 2, 3 and 4 in Fig. 168.

CHAPTER VIII

CYCLONES AND ANTICYCLONES, OR STORMS AND SUNSHINE

SUMMARY

The origin of cyclones and anticyclones is considered and an explanation of their origin is found in the contrasts of temperature observed when large bodies of cold air lie in close proximity to warmer air. These conditions exist permanently or for months at a time where cold continents lie near warmer oceans or cool oceans lie near heated land surfaces. They are found temporarily when large masses of cold polar air come in contact with equatorial currents; that is, with air having a poleward component of motion. These are the conditions in which are found the moving cyclones and anticyclones in the atmosphere.

It is pointed out that where there is a sharp contrast of temperature the greatest pressure gradient is found at a height of about 8000 meters and at that height the tendency of the air motion is from the warm to the cold air column. When readjustment of the pressure takes place by the warmer air flowing over on to the colder air, the pressure increases at the base of the cold column so that there is a pressure gradient at the earth's surface and also a pressure gradient at a height of 20,000 meters, both of which carry the air from the cold column toward the warm column. This fact is shown by means of tables in which the observed temperatures and air densities at different heights are used in the computations.

From the computed pressure gradients, wind velocities are computed which are shown to agree reasonably well with observed wind velocities. The resultant differences of pressure for given temperature gradients are shown to agree with the observed differences of pressure in the permanent cyclones and anticyclonic systems, as well as in the moving cyclonic and anticyclonic systems.

Every cyclone is supposed to have an attendant anticyclone, and since the observed difference of pressure between the two agrees well with that which the computations from the data in the table would lead one to expect, it is considered to be proven that the temperature contrast furnishes sufficient energy to explain the origin of the cyclone and its attendant anticyclone.

The polar cyclone and the general circulation are also briefly reconsidered in the light of the maximum gradient existing at 8000 meters developed by the contrast of temperature between equator and poles.

When the weather conditions are charted on maps, it is found that outside the tropics the surface winds are continually in circulation around central areas, circular or elongated. In one case the wind is inclined inward toward the central area, in the other it is inclined outward. The first has been called a

cyclone, the second an anticyclone. These are usually designated on weather maps by the words "low" and "high," or their equivalents. The first is characterized by cloudy and rainy weather but not necessarily by strong winds and the second by clear skies and sunshine, although under certain conditions, thin, low clouds of the stratus type may be present. These circulations cover large areas, frequently being 1000 miles (1600 km.) in diameter, and if plotted on actual scale within the width of the page of a book their vertical height would be so small that it would be represented by the thickness of the thinnest paper.

In such a condition the vertical gradient of temperature or the lapse rate, can have no important influence in causing the circulation of air, as is the case in local storms where the whole process from the formation of the cumulus cloud to its most imposing development into a thunderstorm or a tornado can be satisfactorily explained by steep vertical gradients of temperature and the behavior of moist air when cooled by expansion.

This conclusion is further strengthened by the fact that cyclones are not most frequent nor most intense when the lapse rate is greatest. Namely, in spring and summer. Neither can the cyclones of temperate latitudes be considered to result from the warmth of central areas and the ascent of large volumes of warm, moist air because the main body of the cyclone is cold and cyclones are not most frequent over land areas in summer, when moisture is most abundant and the sun's heating effect is greatest.

In discussing cyclones and anticyclones in 1900 (Bulletin No. 1, 1900, Blue Hill Observatory) it was pointed out that cyclones are frequently developed along the front of cold waves, and since they are most frequent in winter, they probably owe their origin to differences in temperature in a horizontal direction, that is, to horizontal contrasts of temperature. Other investigators have reached similar conclusions. Margules computed the energy in a squall on that supposition and Brooks[1] has given examples of the development of a secondary cyclone in the United States as a result of such contrasts.

Examination of the data reveals the fact that cyclones in temperate regions are always associated with contrasts of temperature. The permanent low pressures in the atmosphere are all found in regions where there are marked contrasts of temperature, usually between land and water. The cold land mass of

[1] Brooks, C. F.—*Monthly Weather Review*, Vol. 49, pp. 12-13, Washington, Jan., 1921.

Greenland is near the warm waters of the Gulf Stream and the result is a very steep, horizontal gradient of temperature, especially in January, with which is associated an area of low pressure southeast of Greenland. Similar conditions exist in the northern Pacific, where the warm water of the ocean close to cold land surfaces produces steep temperature gradients, associated with low pressure over the water. In the latitudes of about 20° to 30° sharp contrasts of temperature between continent and ocean are found on the west side of the continents in both hemispheres, especially in summer (July in the northern, and January in the southern hemisphere). Further south, near the Antarctic continents, very steep horizontal gradients of temperature are found between the waters of McMurdo Sound and Weddell Sea and the adjacent land, and in both cases a deep barometric depression is found over the water near the steepest temperature gradient, while a belt of low pressure encircles the entire Antarctic continent.

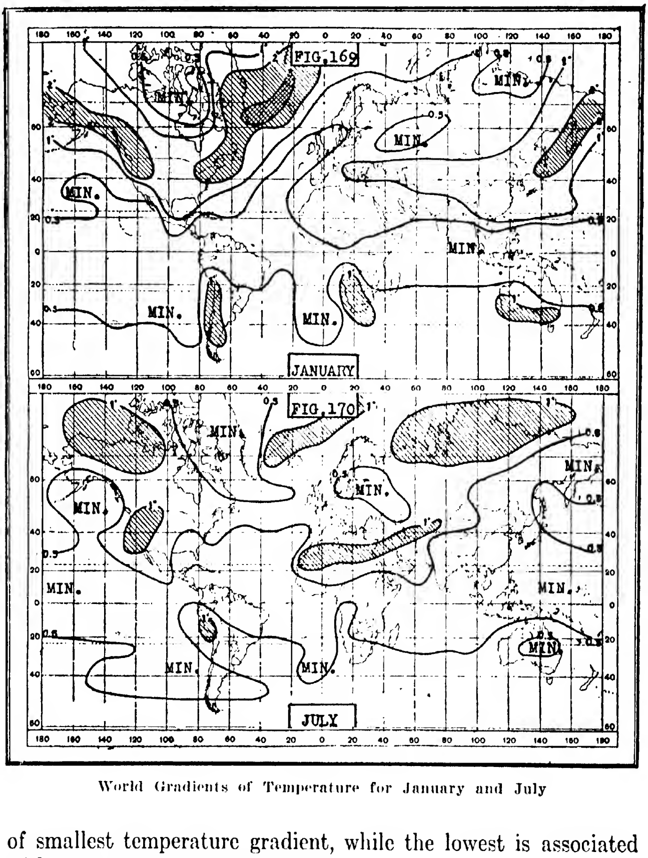
In every case the lowest pressure at the earth's surface is found on the side of the temperature gradient where the temperature is highest. When the temperature is highest over the water, the pressure is lowest over the water as near Greenland, the Aleutian Islands, McMurdo Sound and Weddell Sea; but, when the temperature is highest over the land, the pressure is lowest over the land as in Arizona, northwestern Argentina and southwestern Africa in January, and northern Africa and south central Asia in July.

In the upper air above 10,000 feet (3 km.) the lowest pressure is found on the cold side of the temperature contrast, as may be ascertained by reducing the observed pressure to these levels. In the tropics the pressure is less dependent on temperature contrast and the lowest pressure is observed over the warmest water which extends from the western Pacific into the Indian Ocean. Included within this low area is the low pressure formed over the warm land surface of northern Australia, which in summer embraces the whole Australian continent.

The relation of the low pressures outside the tropics to horizontal temperature gradients is shown in Figs. 169 and 170. The intensities of the gradient at right angles to the lines of temperature were read from the charts of Buchan and Mohn for each ten degrees of latitude between 80° N. and 60° S. and reduced to degrees of temperature change per degree of latitude. Lines of equal temperature gradient were then drawn. The areas of steep gradient are shaded, and the maxima are indicated by

crossed lines, the letters MIN show the positions where the gradient is least. The numbers at the ends of the lines of equal gradient are in degrees Centigrade.

Outside the tropics the highest pressure is found in the region



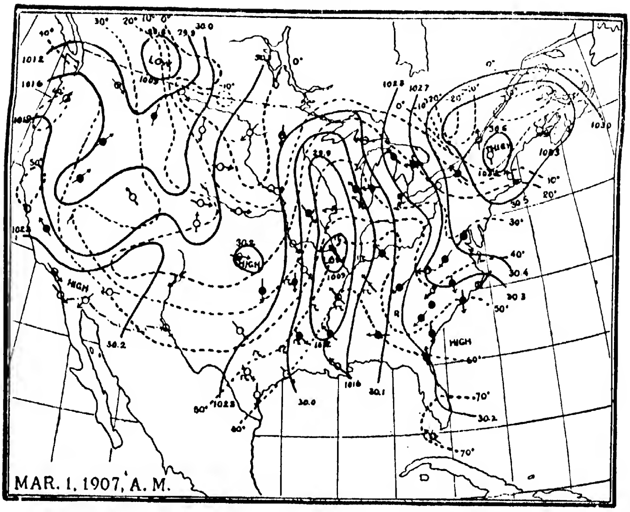
World Gradients of Temperature for January and July

of smallest temperature gradient, while the lowest is associated with steep temperature gradients.

That the traveling low-pressure areas (cyclones) in every part of the world are associated with steep temperature gradients is evident from Figs. 169 to 177.

Fig. 171 shows the weather map for 8 A. M. of March 1, 1907,

FIG. 171



Weather Map of United States. 8 a. m., March 1, 1907

FIG. 172

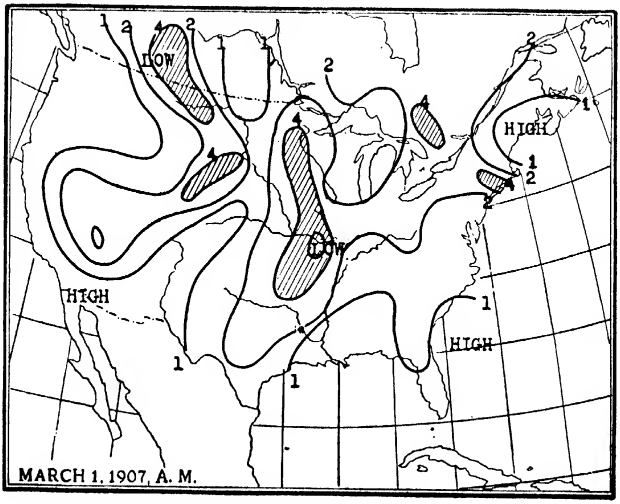
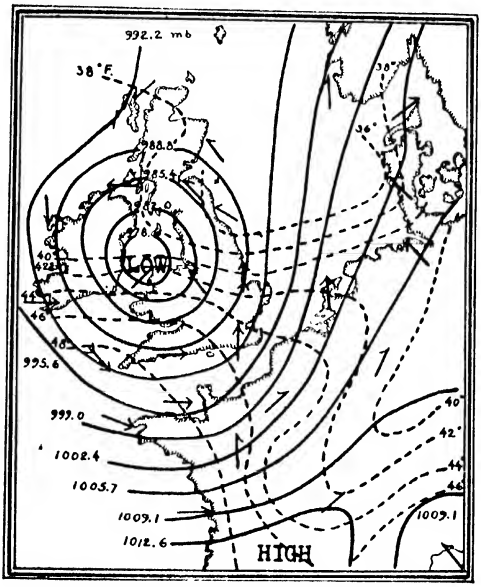


Chart of Temperature Gradients Derived from Fig. 171

in the United States, and Fig. 172 shows the lines of equal temperature gradient for one degree of latitude. The areas of steepest gradient are shaded, and it is seen that steep horizontal gradients of temperature were accompanied by low pressures except in the case of some small areas in Canada and southern New England, where steep gradients are clearly the result of

FIG. 173



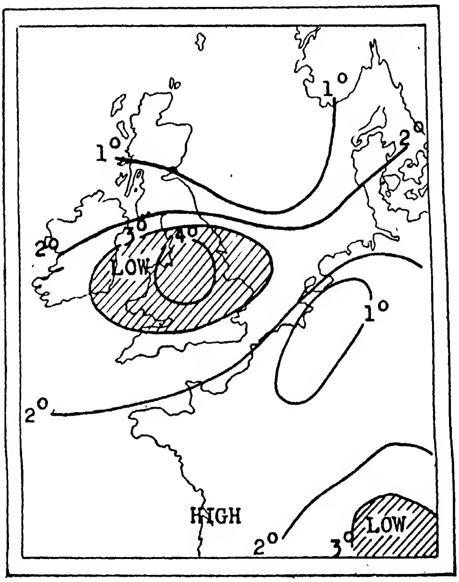
Weather Map of Western Europe
From the Report of the Meteorological Office, London, 6 p. m., 24th March, 1902

local radiation and are purely surface conditions. The three high-pressure areas shown on the chart are all in the regions of small temperature gradient. The lowest pressure in each case was on the warmest side of a temperature gradient. In Missouri it was east of the gradient with the coldest air to the west, while in Montana it was west of the gradient with the coldest air to the east. Fig. 173 shows the weather map for western Europe at 18 h., March 24, 1902, and Fig. 174 shows the lines of equal temperature gradients per degree of latitude. It is seen

that the lowest pressure in the British Isles is immediately west of the steepest gradient and the coldest air is east; while in southern Europe the low pressure is south of the steepest temperature gradient and the coldest air north.

Fig. 175 shows the weather map of Argentina for 8 A. M., May 11, 1921, and Fig. 176 shows the lines of temperature gradient

FIG. 174



Temperature Gradients Derived from Fig. 173

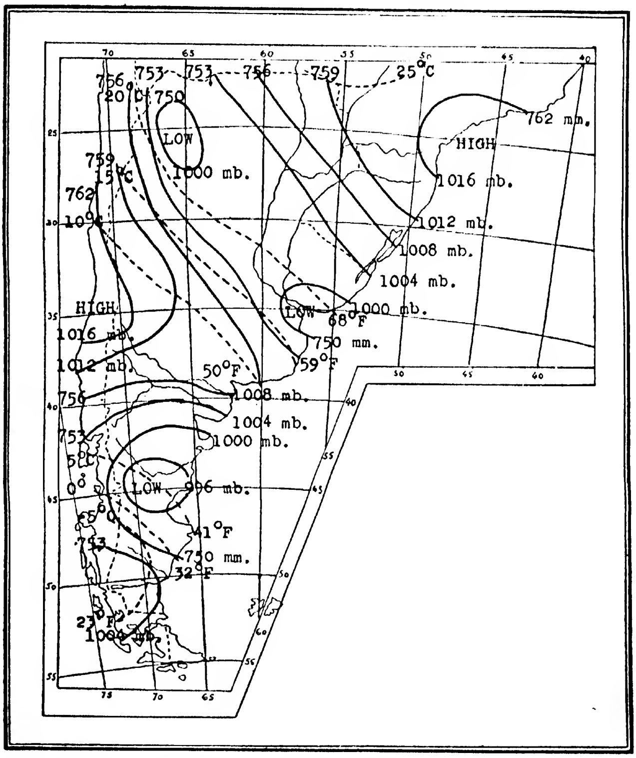
in degrees Centigrade per degree of latitude. Here it is seen that the lowest pressure is north of the steepest gradient and the coldest air south, while the highest pressure is in the region of smallest temperature gradient.

Fig. 177 shows a composite plot of the mean temperature and pressure in cyclones and anticyclones at Blue Hill, Massachusetts (42° N., 71°W.).

The next step was to study the changes of pressure in a vertical direction within areas of temperature contrast. It is known from

laboratory experiments that, under standard conditions, air expands $\frac{1}{273}$ part of its volume (0.00366) for every increase of 1° C. (1.8° F.). Hence, if there are two columns of air near each other of equal area, one at 0° C., and another 1° C. (1.8° F.) warmer

FIG. 175



Weather Map of Argentina, 8 h., May 11, 1921. Sea-level Temperature and Pressure

than the other, the warmer column will be expanded upward and will be 3.66 meters higher than the colder column at an altitude of 1000 meters (about 3300 ft.). For every additional increase of altitude the air will be expanded proportionately

FIG. 176

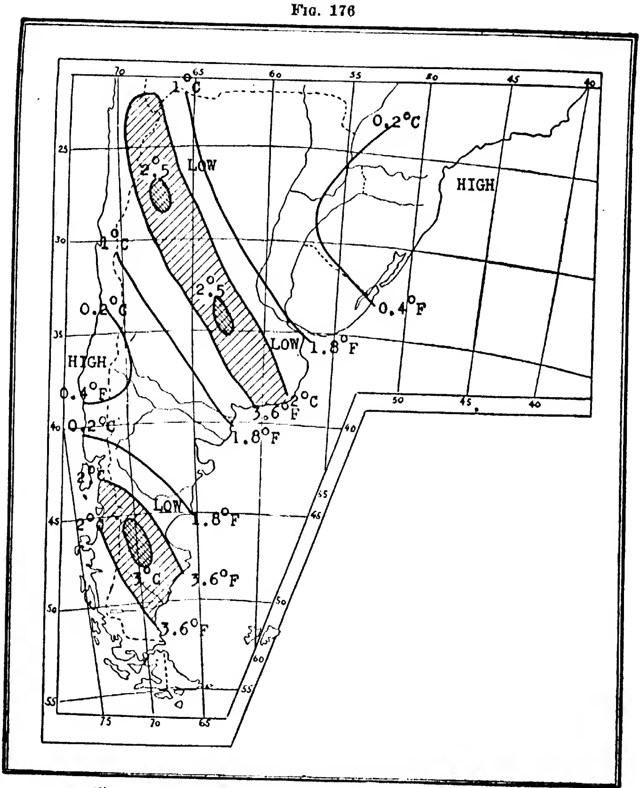
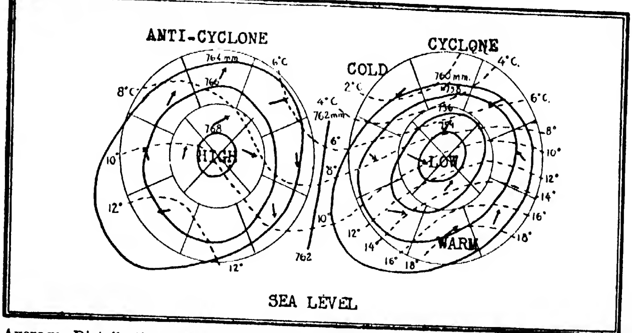


Chart of Temperature Gradients Derived from Fig. 175

FIG. 177



Average Distribution of Pressure, Temperature and Winds in Cyclones and Anticyclones at Blue Hill, Mass.

more. One 2000 meters (about 6600 ft.) high would be expanded twice as much, one 3000 meters (about 10,000 ft.) high three times as much, etc. Hence, if the air were of uniform density, the upper part of the warm column would be lifted by vertical expansion in proportion to the length of the air column, so that the difference of pressure between the cold and the warm columns would be greatest in the highest levels.

But pressure also depends on air density. When the density is twice as great, the pressure is twice as great and when the density is small the pressure is small. In an atmosphere where the density decreases with height a very long air column near the top would give very little pressure.

It is evident, then, that if in such an atmosphere there are two adjacent columns of air both of which cover the same amount of area and exert the same pressure at sea level, but one of which is warmer than the other there will be some level between sea level and the upper part of the atmosphere where the difference of pressure between the two columns will be at a maximum. In order to compute at what height this occurs under standard conditions, Tables XIV to XVII were constructed. In columns 1 and 2 of these tables is given the height in miles and in kilometers, in column 3 is given the progressive upward expansion (h) of the air for 1.0° C. (1.8° F.) difference in temperature for every thousand meters up to 12 kilometers (7.5 mi.) and for greater intervals up to 30 kilometers (19 mi.), in column 4 is given the density (ρ) of the air at each successive level as derived from several hundred balloon ascents in Europe,[2] in column 5 is given the relative density (ρ_r), taking the sea-level density as unity. In column 6 the height of the expanded air (h) given in column 3 is multiplied by the relative density (ρ_r) given in column 5 so as to obtain a column of equivalent height at sea level. Thus a column of 30 meters near 6 kilometers would have only half the density of one at sea level and the pressure at its base would be equivalent to a column of 15 meters at sea level, which is given in column 6 as the product of the height by the density (30 x 0.5). Having reduced the air columns to equivalent columns of standard density ($\rho_r h$), the next step was to compute the pressure exerted by the columns at different levels in the atmosphere. This was accomplished by finding what would be the pressure of each meter of air at standard density and multi-

[2] W. J. Humphreys—*Physics of the Air*, p. 72, Philadelphia, 1920.

plying this by the air columns given in the table reduced to standard density. The height of an atmosphere of uniform density at standard pressure, temperature and gravity is 7991 meters and the pressure of an atmosphere is 1013 millibars, so that 1013 divided by 7991 gives the pressure of one meter of air at standard density, and this multiplied by the heights of the various air columns at standard density gives the pressure in each case.

Expressed mathematically,

$$dp = \frac{1013\ \rho_r h}{7991} = 0.1268\ \rho_r h$$

These pressures are given in Tables XIV to XVII in column 7 under dp and the numbers show the remarkable fact that when two columns of air at different temperatures are near each other the greatest difference of pressure is at a height of about 8000 meters.[3]

But, when at any level there is a difference of pressure between two adjacent columns, the air will flow from one to the other in the effort to establish equilibrium and, if the difference of tem-

[3] This same fact was shown mathematically by Professor W. J. Humphreys in *Physics of the Air*, p. 157. He says: "The approximate level of the maximum horizontal gradient may be found as follows:

As just explained, in the equation,

$$-\frac{dp}{dn} = \frac{pa\Delta Th}{HL}$$

the factor $\frac{a\Delta T}{HL}$ is roughly constant. Writing G for the gradient, K for the constant, the equation takes the form,

$$G = Kph$$

Hence G has a maximum value when

$$pdh = hdp$$

but,

$$-dp = p\frac{dh}{H}$$

Hence the pressure gradient is steepest when

$$pdh = \frac{h}{H}pdh$$

that is when $h = H = 8$ kilometers roughly."

In these equations p is the pressure, dp the difference in pressure and dn the distance, ΔT is the difference in temperature, h is the height of the air column, and H the height of a homogeneous atmosphere, about 8 kilometers (or more exactly 7991 meters), a is the coefficient of volume expansion of air for 1° C. rise of temperature.

perature persists, it is reasonable to suppose that the mean difference of pressure between the two columns will be equalized, so that as much air moves toward one column as toward the other. For this reason, it is assumed that when the difference of temperature persists after the circulation is established, the difference of pressure will be divided between the warm and the cold column, the pressure gradient at 5 miles (8 km.) being directed from the warm toward the cold column, and at sea level from the cold toward the warm column. The overflowing air will cause the pressure to rise at the base of the cold column and to fall at the base of the warm column. Hence, one half the difference of pressure at 8000 meters is subtracted from the warm column and added to the cold column to produce a balanced system. In this manner are obtained the differences represented in the last column (*dpw*) of the table. In this column the minus sign indicates that the pressure gradient is from the cold to the warm column.

Three cases are considered: (1) The case in Table XIV, in which the difference of temperature between the adjacent columns of air continues up to 11 kilometers (7 mi.) and then ceases, which appears to approximate the actual condition in the atmosphere. (2) The case in Table XV, where the difference in temperature between the adjacent columns of air continues up to 30 kilometers (19 mi.). (3) The case in Table XVI, where the temperature difference between the adjacent air columns continues up to 11 kilometers (7 mi.) and then reverses direction which is supposed to be the case in cyclones and anticyclones. (4) The case in Table XVII, where the difference between the columns continues up to 8 kilometers (5 mi.) and then reverses direction, which may occur in northern Europe (about latitude 70°). In each case the mean difference between the columns is taken as 1° C., or 1.8° F.

As the computations for the lower 8 kilometers are the same for Tables XV, XVI and XVII as for Table XIV the results for these levels are not repeated. Altering the mean temperature of the air columns would change these values somewhat, but the values in the final column *dpw* would not be changed appreciably within the limit of observed temperatures.

It will be noted from the last column *dpw* in Table XIV that the pressure gradient is directed from the cold column toward the warm column at sea level, at 1000 meters and at 2000 meters; but at 3000 meters, the sign changes and the pressure gradient is directed from the warm to the cold column. This condition

TABLE XIV

Computed Pressure Gradients for 1° C. Differences in Temperature of Air Column with Constant Difference of Temperature up to 11 Kilometers (7 Miles) and no Difference at Higher Altitudes.

Miles	*Km.*	*h* *Meters*	*Densities* ρ	*Densities* ρ_r	$\rho_r h$	*Pressure Gradients* *dp*	*Pressure Gradients* *dpw*
0.0	0	0.000	1256.0	1.000	0.000	0.000	—0.782
0.6	1	3.663	1123.4	0.886	3.245	0.411	—0.371
1.2	2	7.326	1010.1	0.804	5.890	0.747	—0.035
1.9	3	10.989	908.8	0.724	7.956	1.008	0.226
2.5	4	14.652	817.3	0.651	9.538	1.209	0.427
3.1	5	18.315	735.0	0.585	10.714	1.358	0.576
3.7	6	21.978	659.9	0.525	11.538	1.463	0.681
4.4	7	25.641	591.7	0.471	12.077	1.531	0.749
5.0	8	29.304	528.8	0.421	12.337	1.564	0.782
5.6	9	32.967	470.2	0.374	12.329	1.562	0.780
6.2	10	36.630	414.6	0.330	12.088	1.532	0.750
6.9	11	40.293	361.9	0.288	11.604	1.471	0.689
7.5	12	"	311.2	0.248	9.993	1.267	0.485
8.8	14	"	228.0	0.182	7.333	0.926	0.144
10.0	16	"	167.0	0.133	5.359	0.679	—0.103
11.2	18	"	122.4	0.097	3.908	0.496	—0.286
12.5	20	"	89.7	0.071	2.861	0.363	—0.419
15.6	25	"	41.3	0.033	1.330	0.169	—0.613
18.7	30	"	19.0	0.015	0.604	0.077	—0.705

h = Difference in height of adjacent air columns for 1° C. (1.8° F.) difference in temperature, the mean temperature of the air column being taken as 0° C.
ρ = Air density in grams per cubic meter. (From balloon observations in Europe, after Humphreys.)
ρr = Relative density, or ratio to sea-level density.
ρrh = Product of relative density by difference in height to reduce to same air mass.
dp = Difference of pressure resulting from differences of height of air column, ρrh.
dpw = Differences of pressure in warm air column equal total difference dp less one half of maximum (at 8 km.).

TABLE XV

Computed Pressure Gradients with Constant Difference of Temperature of 1° C. between Adjacent Air Columns up to a Height of 30 Kilometers (19 Miles).

Miles	*Km.*	*h* *Meters*	*Densities* ρ	*Densities* ρ_r	$\rho_r h$	*Pressure Gradients* *dp*	*Pressure Gradients* *dpw*
6.2	10	36.630	414.6	0.330	12.088	1.532	0.750
6.9	11	40.293	361.9	0.288	11.604	1.471	0.689
7.5	12	43.956	311.2	0.248	10.901	1.382	0.600
8.8	14	51.282	228.0	0.182	9.333	1.182	0.401
10.0	16	58.608	167.0	0.133	7.795	0.988	0.206
11.2	18	65.934	122.4	0.097	6.396	0.810	0.028
12.5	20	73.260	89.7	0.071	5.201	0.659	—0.123
15.6	25	91.575	41.3	0.033	3.022	0.383	—0.399
18.7	30	109.890	19.0	0.015	1.648	0.209	—0.573

TABLE XVI

COMPUTED PRESSURE GRADIENTS WITH CONSTANT DIFFERENCE OF TEMPERATURE OF 1° C. IN AIR COLUMNS UP TO 11 KILOMETERS (7 MILES) AND REVERSE GRADIENT OF 1° C. AT GREATER HEIGHTS.

Miles	*Km.*	*h* *Meters*	*Densities*		$\rho_r h$	*Pressure Gradients*	
			ρ	ρ_r		*dp*	*dpw*
6.2	10	36.630	414.6	0.330	12.088	1.532	0.750
6.9	11	40.293	361.9	0.288	11.604	1.471	0.689
7.5	12	36.630	311.2	0.248	9.084	1.151	0.369
8.8	14	29.304	228.0	0.182	5.333	0.676	— 0.106
10.0	16	21.978	167.0	0.133	2.923	0.244	— 0.538
11.2	18	14.652	122.4	0.097	1.421	0.180	— 0.602
12.5	20	7.326	89.7	0.071	0.520	0.066	— 0.716
15.6	25	— 10.989	41.3	0.033	— 0.362	— 0.046	— 0.736
18.7	30	— 29.304	19.0	0.015	— 0.440	— 0.056	— 0.726

agrees remarkably well with the conditions found at Blue Hill,[4] where the observations with kites show that the lowest pressure is on the warm side of the steepest temperature contrast up to 2000 meters, while from 3000 meters to 9000 or more the lowest pressure is on the cold side of the gradient. In other words, the surface cyclone has a warm center, while the cyclone above 2 kilometers has a cold center.

At heights above 15 kilometers the gradient again changes sign and is directed from the cold toward the warm column. The only difference in the four cases in Tables XIV to XVII is in the height of the maximum gradient in the reverse direction to the gradient at 8 kilometers. If the difference of tempera-

[4] Blue Hill Meteor. Observatory, Exploration of the Air with Balloons-sondes and Kites, Plates VIII and IX, *Annals of the Astronomical Observatory of Harvard College*, Vol. 48, Pt. 1, Cambridge, Mass., 1909.

TABLE XVII

COMPUTED PRESSURE GRADIENTS WITH CONSTANT DIFFERENCE OF TEMPERATURE OF 1° C. IN AIR COLUMNS UP TO 8 KILOMETERS (5 MILES) AND REVERSE GRADIENT OF 1° C. AT GREATER HEIGHTS.

Miles	*Km.*	*h* *Meters*	*Densities*		$\rho_r h$	*Pressure Gradients*	
			ρ	ρ_r		*dp*	*dpw*
0.0	0	0.000	1,256.0	0.000	0.000	0.000	— 0.782
5.0	8	29.304	528.8	0.421	12.337	1.564	0.782
10.0	16	0.000	167.0	0.133	0.000	0.000	— 0.782
15.6	25	— 32.967	41.3	0.033	— 1.088	— 0.138	— 0.644
18.7	30	— 51.282	19.0	0.015	— 0.769	— 0.097	— 0.685

ture between the adjacent air columns did not reach 8000 meters, the maximum gradient would occur where the temperature difference ceased, and in the case of the diurnal heating of a land surface the maximum gradient would not exceed 1 or 2 kilometers (about 1 mi.).

It remains now to ascertain: (1) whether the gradients thus computed in column *dpw* of the tables agree with the pressure gradients observed in the regions of contrasts of temperature in the atmosphere, and (2) whether the computed velocities derived from such pressure gradients accord with observed velocities of air circulation in the part of the atmosphere where friction is small.

PERMANENT CYCLONES AND ANTICYCLONES OF THE ATMOSPHERE

Considering first the permanent cyclones and anticyclones of the atmosphere, differences of temperature between the two sides of the steep temperature gradients shown on the charts of Buchan [5] were obtained for all parts of the world. These differences are tabulated below for the two months of January and July. The differences were read from the center of the low pressure to the coldest point in the rear of the contrast of temperature in the direction of the gradient (at right angles to the lines of equal temperature). Thus the difference of temperature was

[5] Buchan, A.—*Report on the Scientific Results of the Voyage of H.M.S. Challenger,* Physics and Chemistry Series, Vol. 2, Part 5, London, 1889.

TABLE XVIII

COMPARISON OF OBSERVED PRESSURE WITH PRESSURE COMPUTED FROM TEMPERATURE GRADIENTS

January	*Temperature Gradient*		*Difference of Pressure*		
			Computed	*Observed* (1)	*Observed* (2)
S. Greenland coast to N. Canada	36° C.	65° F.	28 mb.	18 mb.	26 mb.
Aleutian Islands to N. E. Siberia	50	90	39	29	36
Central Brazil to Pacific Coast	11	20	9	7	12
N. Australian to southern coast	17	30	13	9	17
July					
Arizona to Pacific Coast	20	35	16	12	19
Arabia to N. Atlantic Coast	25	45	20	20	27

obtained from the center of the low pressure south of Greenland to the coldest region in Canada west of Greenland, from the center of the Aleutian low to the cold region in northeastern Siberia, from the low pressure in the warm region of Arizona to the lowest isotherm off the coast of southern California and from the Arabian low to the northern coast of Europe.

The pressure difference was computed from the difference *dpw* at the earth's surface given in the last column of Table XIV as —0.782 for 1° C. This factor was multiplied by the observed temperature differences to get the pressure differences to be expected from the observed contrast of temperature. Thus between the south Greenland coast and northern Canada there is a temperature difference of 36° C. (65° F.) which multiplied by 0.782 gives the pressure difference of 28 millibars. The observed pressure difference shown by the chart is 18 millibars; but as the highest pressure is not at the place of lowest temperature a second reading is obtained for the difference between the lowest pressure near Greenland and the highest pressure in Canada and the difference is found to be 26 millibars. That the highest pressure is not at the place of lowest temperature is clearly because a centrifugal force, $\frac{v^2}{r}$ is developed by the circulation of the air around the cold-center cyclone in the upper air, as a result of which the air is carried away toward the region of small temperature contrast where an area of high pressure is developed, partly as the result of dynamic causes and partly because of low temperature at the base of the air column. However, as the whole of the energy for the formation of both the high pressure and the low pressure must be derived from the temperature gradient, it is proper to compare the total pressure difference with that computed from the temperature contrast. Hence, as the computed pressure gradient of 28 millibars is slightly greater than the pressure difference between the highest and lowest pressure, 26 millibars, it proves that the horizontal temperature contrast is capable of causing the whole of the pressure difference.

The computed difference of pressure for the temperature difference between the Aleutian Islands and Siberia is 39 millibars while the observed difference between the low pressure in the ocean and the highest pressure on the land is 36 millibars, showing again that the temperature contrast is capable of explaining the whole of the difference. The computed pressures from the contrasts in southern latitudes are near to, but slightly below, the

observed pressure differences. This arises probably from the greater difficulty of determining the full temperature contrast from the isothermal lines, or else from an increasing tendency for low pressure to form in the warmest regions independent of local contrasts as the equator is approached. The data are not sufficient to permit the computation of the pressure differences resulting from the very steep temperature gradients in Weddell Sea and McMurdo Sound and the Antarctic continent.

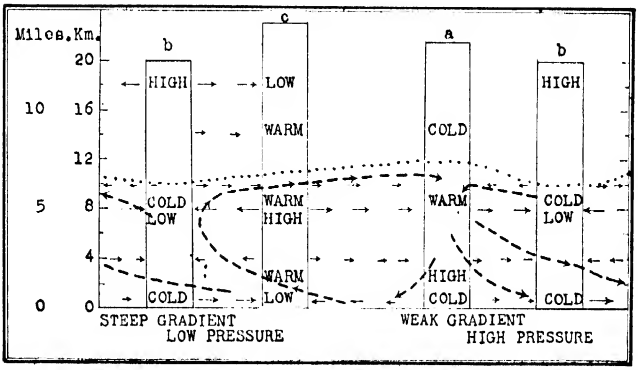
In the United States on March 1, 1907 (Fig. 171) the temperature gradient between the Mississippi valley and the high pressure in Nebraska was 40° F., or 22.5° C., which according to the computed gradients in column *dpw* of Table XIV ought to give a pressure difference between the high and low of the product of $0.782 \times 22.5 = 17.6$ millibars, while the observed difference is 14 millibars. In the region of Montana, the difference in temperature is 30° F., or 18.8° C., which would give a pressure difference of 14.7 millibars, while the observed difference is 11 or 14 millibars, according as it is taken from the higher pressure to the east or to the south. In Argentina on May 11, 1921 (Fig. 175) the contrast of temperature was 16° C., which would give a difference of pressure of 12.5 millibars, while the observed difference was 12 millibars. In every case the gradient to be expected from the temperature contrast was sufficient to explain the pressure difference. The map for Great Britain, Fig. 173, does not cover sufficient area to give the total temperature gradient.

As the surface gradient cannot be taken as expressing the full extent of the temperature contrast which is frequently greater at considerable altitude than near the ground, there are sometimes cases where the difference exceeds the computed values, even though the theory is correct.

A generalized scheme of the circulation in a vertical section of an atmosphere undisturbed by other conditions is presented in Fig. 178. A column of air of equal cross-section is taken on either side of the steep gradient of temperature. The column *b* is on the cold side of the gradient and the air is cold up to a height of at least 11 kilometers (7 mi.), while *c* is on the warm side and the air is warmer than *b* up to 11 kilometers. According to the data given in column *dpw* of Table XIV, there should be a pressure gradient and a flow of air from the cold column toward the warm column up to 2 kilometers and then a pressure gradient from the warm column toward the cold column increasing to a maximum at 8 kilometers. Hence, surface air entering on the warm side of the gradient would ascend over the cold surface

wind and be carried inward by the pressure gradient toward the low pressure of the upper air in the rear of the temperature gradient. At some height below 8 kilometers this inflow is checked by the centrifugal force generated by the circulation. The air is rising, first and chiefly, because it is warm and, secondly, because there is a small component of the earth's centrifugal force tending to lift it when it turns into a current from the west. It has an inward component of motion toward the low pressure, because in rising it has a less velocity than is

Fig. 178



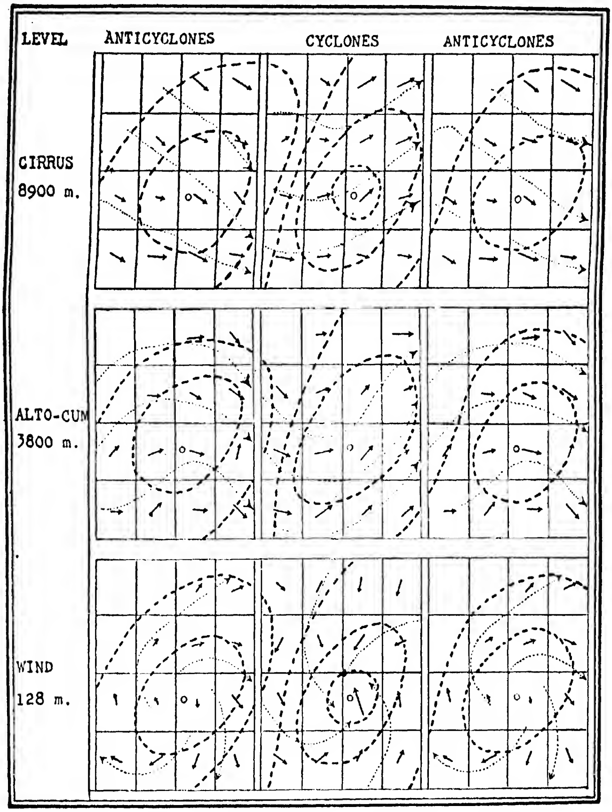
Pressure and Wind in a Vertical Section in the Atmosphere Resulting from Differences of Temperature in Adjacent Columns of Air

needed to balance the increasing gradient of pressure which, as shown above, increases until the height of 8 kilometers is reached. Above that height the wind has a velocity greater than is needed to balance the decreasing gradient and, hence, will be carried out by centrifugal force against the gradient. Passing outward from the region of steep temperature gradient with diminishing velocity, the air arrives at a region of weak temperature gradient where it encounters a back flow from the preceding cold-air cyclone and builds up an area of high pressure, partly as a result of dynamic causes and partly as a result of cold air near the ground. From this point of view, the surface cyclone on the warm side of the steep temperature gradient, the cold-air cyclone in the rear and the high-pressure area are all built up by the energy derived from the temperature contrast. The cloudy and rainy weather observed within regions of temperature contrast

also finds a satisfactory explanation in the ascending and cooling warm air.

Fig. 179 shows the mean movements of the air over New England in cyclones and anticyclones. In the upper part of the

Fig. 179



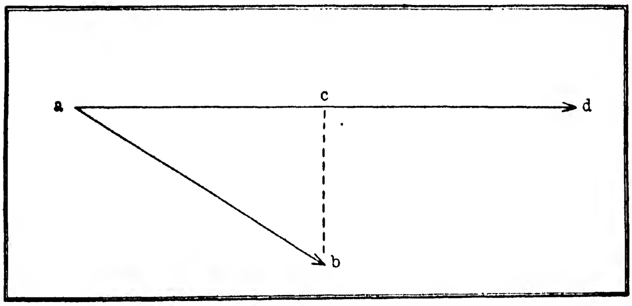
Movement of Air at Different Heights in Cyclones and Anticyclones

diagram, the mean motions of the cirrus and cirro-stratus clouds are given in five degree squares around the centers of cyclones and anticyclones. In the middle part of the diagram the mean motions of the alto-cumulus and alto-stratus are given and in

the lower part are given the mean motion of the winds. These results are derived from many hundreds of observations at Blue Hill, Massachusetts, 42° N., 71° W. The arrows show the mean directions and relative strength of the currents in each square, broken lines show the isobars at sea level and the dotted lines show the stream lines which may be taken as isobars at the level of the upper currents. At the earth's surface, the lowest pressure is at the center of the cyclone, while at the level of the alto-cumulus it is to the northwest of the center.

In order to eliminate the general drift of the atmosphere, the mean drift was computed from the whole of the observations;

FIG. 180



Method of Determining Wind Components

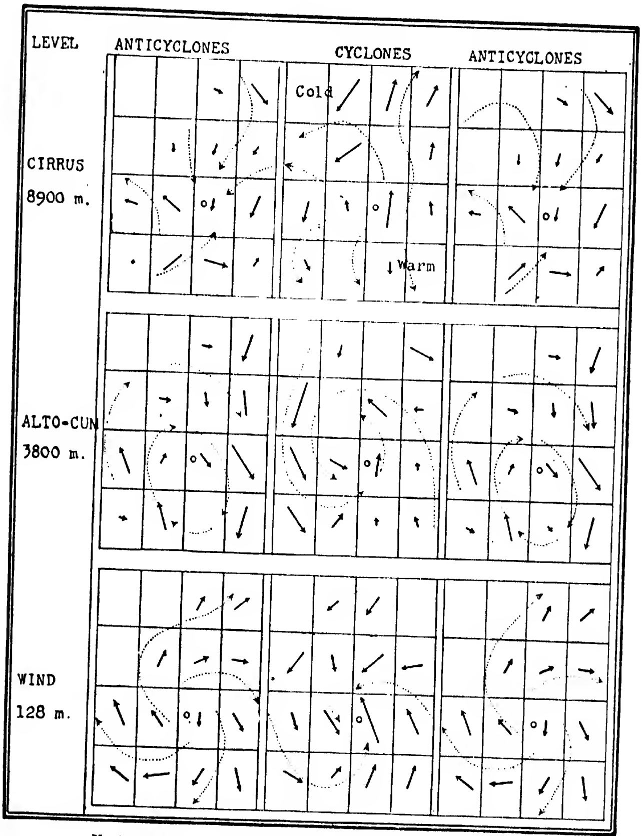
then plotting this general mean in connection with the mean directions obtained for each part of the cyclone and anticyclone it was possible to obtain the cyclonic components of motion. Thus, in Fig. 180 let *ac* represent the mean drift from the west and *ab* the drift observed in any given part of a cyclone, then *cb* will represent the cyclonic component, or vector wind, for that part.

In this way the mean directions given in Fig. 181 were obtained. These diagrams show clearly that the air streams outward from the anticyclone and inward to the cyclone at the earth's surface and streams outward from the cyclone and inward toward the anticyclone in the cirrus level. It should be noted also that there is a component of motion in the cirrus level from the cold-air cyclone of the upper air toward the center of the anticyclone.

The movement of the air in cyclones as found by Sir Napier

Shaw [6] and R. G. K. Lempfert apparently agrees with this conception of the cyclone. The movement of the wind was followed from point to point by these authors from observations at intervals of two hours, the velocity and direction of the wind giving

FIG. 181



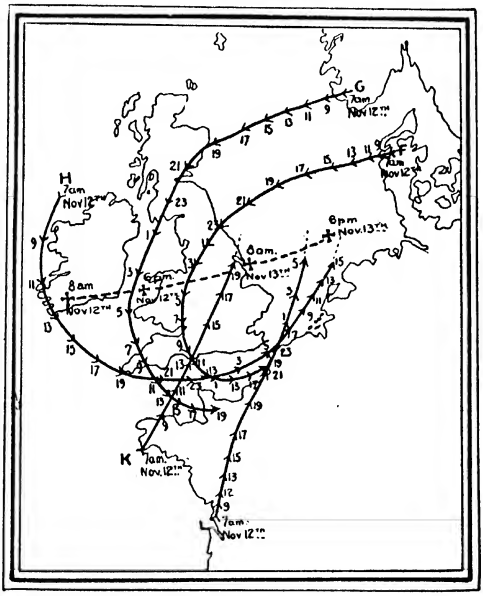
Vector Winds in Cyclones and Anticyclones at Blue Hill

the clue to this progress. Fig. 182 gives the trajectories of the air in a cyclone which crossed the British Isles on November 12

[6] Shaw, W. N. and Lempfert, R. G. K.—"The Life History of Surface Air Currents," *Meteor. Office Publication,* No. 174, London, 1906.

to 13, 1901. The track of the cyclone center is shown by the broken line, and the wind trajectory by the joined arrows. It is seen that the warm southerly wind moved up from the west coast of France to the track of the cyclone and disappeared, undoubtedly rising above the cold currents to the north, while the cold air moved around the cyclone and followed in its rear.

FIG. 182



Trajectories of Wind in Cyclone in British Isles, Nov., 1901—After Shaw and Lempfert

The theory also sufficiently accords with the views of Bjerknes previously mentioned.

It remains now to ascertain whether the observed wind velocities in the part of the atmosphere where friction is small agree with the gradient computed from column *dpw* of Table XIV. My observations of the velocity of the cirrus clouds in different temperature gradients at Blue Hill serve very well for this purpose.

The results of the observations were as follows:

TABLE XIX

VELOCITY OF CIRRUS COMPUTED FROM THE TEMPERATURE GRADIENT

Latitude of Blue Hill 42° 13′ N., Long. 71° 6′ W.; sin $\phi = 0.672$.

Number of isotherms of 10° F. within 250 miles (3°.62 of lat., see Chapter IV, p. 131)	1	2	3	4
Temperature gradient in degrees Fahrenheit..	10	20	30	40
Temperature gradient in degrees Centigrade..	5.6	11.1	16.7	22.2
Mean observed velocities of cirrus clouds, meters per sec.	39	48	55	59
Number of observations......................	36	66	41	7
Temperature gradient in degrees C. per 1° lat.	1.5	3.1	4.6	6.1
Heights of cirrus in kilometers..............	9.5	9.0	8.6	8.2
Atmospheric pressure at height of cirrus (mb.)	277	299	317	337
Temperature at height of cirrus (° C.)........	—39	—42	—46	—50
Pressure gradient for 1° lat. Computed from 0.782 mb. per 1° of temperature gradient *.	1.2	2.4	3.6	4.7
Computed velocity at cirrus level †..........	28	49	67	81

* See Table XIV, column *dpw*.
† The computed velocities of the cirrus were obtained by means of the formulas given in Appendix A.

As gradient 1 was observed mostly in summer and gradient 3 in winter the mean summer height of the cirrus was taken for gradient 1 and the mean winter height for gradient 3 and the mean for the year for gradient 2. As gradient 4 occurs only in severe weather, the cirrus were assumed to be lower than for gradient 3. It is seen that the computed value for the lowest gradient is somewhat lower than the observed value while for the steepest gradients it is too high. There were so few observations for gradient 4 that it may be left out of account. For gradients 1, 2 and 3 the total number of observations was 143 and the mean velocity 47 meters per second, while the mean computed velocity is 48 meters per second. This seems a satisfactory agreement. Friction was not considered but is known to be small in the free air.

Thus both the pressure differences between cyclones and anticyclones and the energy, as represented by the velocity of the air in motion, seem fully accounted for by the energy derived from contrasts of temperature between adjacent bodies of warm and cold air.

The permanent cyclones are caused by the constant differences of temperature found in certain regions between land and water and the moving cyclones are caused by temporary contrasts of temperature brought about by masses of cold air moving from the pole to the equator.

Tropical cyclones appear to be somewhat different in origin from the cyclones in temperate latitudes. The tropical cyclone

originates in a region of warm, moist air within the tropics and probably owes its origin to differences in temperature between a central area and the surrounding air. Its energy is accounted for by the heat liberated by the abundant condensation of moisture. Hann [7] has made a calculation of the amount of energy involved and finds a satisfactory agreement. These storms originate most frequently over the warm waters of the western Atlantic, the western Pacific, and the Indian Ocean within ten or fifteen degrees of the equator both north and south. From their place of origin, they move toward the poles, first curving toward the west and then toward the east at higher latitudes. The change in direction from west to east appears to take place at about latitude 30° in the northern hemisphere and 20° in the southern. These storms were much studied by Blandford and Elliot in India, and by Redfield and Poey in America. E. H. Bowie [8] has recently published a study of the West India cyclones with the newest accessible data and the British Meteorological Office a study of cyclones in all parts of the tropical belt.[9] In these cyclones the centrifugal force developed by the whirl is of more importance than the deflecting force of the earth's rotation. The cause of the progressive movement of cyclones and anticyclones is generally believed to be the general drift of the atmosphere surrounding them at the time. This drift can be inferred with a fair degree of accuracy from the distribution of pressure and temperature in the area surrounding the cyclone.

From the foregoing tables and computations it seems evident that sharp contrasts of temperature in adjacent bodies of air causing steep gradients are fully capable of producing the permanent and the wandering cyclones and anticyclones of the atmosphere in temperate regions. Thus may be explained a large part, perhaps most, of the atmospheric circulation, especially in the months of January and July.

THE POLAR CYCLONES AND THE GENERAL CIRCULATION

But there remains the general contrast of temperature between equator and pole to be considered as forming part of the general

[7] Hann, J.—*Nature*, London, 1921.

[8] Bowie, Edward H.—"Formation and Movement of West Indian Hurricanes," *Monthly Weather Review*, Washington, Vol. 50, April, 1922, pp. 173-179.

[9] Shaw, Sir Napier—"The Birth and Death of Cyclones," *British Meteor. Office Geophysical Memoirs*, No. 19, pp. 213-227, London, 1922.

circulation and the question arises as to what form the atmospheric circulation would assume if there were no adjacent land and ocean surfaces with their sharp contrasts of temperature. As explained in Chapter I, observations are as yet insufficient to permit this problem to be treated decisively, but there are certain physical and mechanical laws which allow the problem to be outlined. In Table XIV it is shown that in two adjacent columns of air of different temperatures there is at first produced a strong gradient of pressure at 8000 meters from the warm toward the cold column and the final adjustment leads to a gradient of pressure from the cold to the warm air in the lowest part of the atmosphere as well as in the highest part. This would lead to a current flowing from the equator to the pole at a height of about five miles (8 km.) and a return current at the surface and at heights above 20 kilometers. But the air at five miles (8 km.) moving toward the pole is deflected by the earth's rotation into a strong west to east circulation around both poles.

Another way of viewing the matter is to compute the effect to be expected from the contrast of temperature between equator and pole as was done in the case of cyclones. From Fig. 101 it is seen that in the northern hemisphere the contrast between equator and pole is 89° F. (48° C.) in the northern hemisphere and is estimated as 102° F. (57° C.) in the southern. As a considerable part of this difference arises from surface cooling near the poles let it be assumed that the mean temperature of the air column near the pole is 72° F. (40° C.) colder than at the equator, then from the data given in the last column of Table XIV the difference of pressure ought to be 40 times 0.782 = 31.2 millibars, which would give a pressure gradient of 0.35 millibars for each degree of latitude toward the pole at 8000 meters and away from the pole at the earth's surface, if the earth were not in rotation. If a uniform pressure gradient from pole to equator is assumed and gradient velocities are computed by the formulas previously given, it is found that no stable system could persist on a rotating earth; because the velocities would become infinite at the equator. The only stable system would be one in which the velocity was uniform from equator to pole or else increased somewhat toward the pole. Assuming a uniform velocity and taking that velocity which would be required to balance the gradient 0.35 millibars at 45° latitude, which is approximately 23 meters per second, the pressure gradients necessary to balance this velocity at each latitude may be computed (see Appendix A).

These computed gradients are given in column 3 of the following table:

TABLE XX

COMPUTED PRESSURE GRADIENT FOR EACH 5° OF LATITUDE, WIND 23 METERS PER SECOND

Latitude	*Sin. φ*	*dp Computed*	*Uniform Gradient*	*Sum*
5°	0.087	−0.04	0.35	+0.31
15	0.259	−0.13	0.35	+0.22
25	0.423	−0.21	0.35	+0.14
35	0.574	−0.28	0.35	+0.07
45	0.707	−0.35	0.35	0.00
55	0.819	−0.41	0.35	−0.06
65	0.906	−0.45	0.35	−0.10
75	0.966	−0.48	0.35	−0.13
85	0.996	−0.50	0.35	−0.15

This table shows that the effect of a uniform wind in the upper layers of the atmosphere would be to change the distribution of pressure in such a manner that its effect added to a uniform gradient such as might be caused by temperature alone would produce a gradient increasing to middle latitudes and then decreasing toward the pole. Owing to the fact that the mass of moving air (velocity multiplied by density) remains the same at all heights from about 1 to 11 kilometers, no correction is needed for change of velocity with height.

In the actual atmosphere the temperature gradient and wind velocity increase as the pole is approached, and the result is a distribution of pressure such as is shown in Fig. 107.

The surface current from about 30° latitude has a component of motion toward the pole and the returning air is in the cirrus region. Owing to the variations in the atmospheric circulation produced by variations in solar energy and changing contrasts of temperature between equator and pole, these cold-air masses come off in pulses from the polar region and produce the cold waves which bring about the moving cyclones and anticyclones of the atmosphere.

CHAPTER IX

SKY COLORS AND VISIBLE SIGNS OF THE SKY AND AIR

SUMMARY

A description and explanation is given of sky colors and of many phenomena visible in the sky, such as rainbows, glories, coronas, halos, scintillation, mirage, auroras, etc. These are a part of weather conditions and are frequently used as prognostics of weather changes for short intervals in advance.

THE beautiful blue of the sky, the subdued twilight, the glorious sunset colors, the brilliant pure tints of the rainbow, the colored circles and bright rings and crosses occasionally seen in the sky, the inverted mirage of the lower air are all part and parcel of the weather and appear or disappear with its changing moods.

The exhaustive studies of Lords Rayleigh, father and son, in regard to the blue of the sky, give them preëminence in this field, and no better description can be given than in the words of the present Lord Rayleigh in a lecture at the Royal Institution on Friday, May 7, 1920.

"Let us begin with one of his [Lord Rayleigh 1st] experiments which illustrates the accepted theory of the blue sky. We have here a glass tank containing a dilute solution of sodium thiosulphate. A condensed beam from the electric arc traverses it and then falls on a white screen, where it shows the usual white color. I now add a small quantity of acid, which decomposes the solution with slow precipitation of very finely divided particles of sulphur. As soon as this precipitation begins you see that light is scattered,—that is to say, it is diverted to every side out of the original direction of propagation. Moreover, you will observe that the scattered light is blue. The transmitted beam is robbed of its bluer constituents and tends to become yellower, as you see on the screen.

"The light scattered laterally is to be compared to the direct light of the setting sun when it has traversed a great thickness of air.

"As the precipitation goes on, the transmitted light becomes orange, and even red. But the particles of sulphur eventually get bigger, and then give a less pure blue in the lateral direction. We shall have more than enough to occupy us if we confine our attention to the earlier stages, when the particles are small compared with the waves of light.

"A very important property of the scattered light is its polarization. The vibrations of the scattered light as you have seen it, viewed laterally in the horizontal plane, are almost wholly up and down. No light is emitted which vibrates in the horizontal plane. It is easy for individual observers to verify this with a Nicol's prism held to the eye, but this direct method unfortunately does not lend itself to public demonstration.

"We may, however, use polarized light to begin with, and you can then observe that if the polarizing Nicol is set so as to transmit up and down vibrations, these are abundantly scattered towards you by the small particles. As I turn the polarizing Nicol through a right angle, you will see that the light scattered towards you is extinguished.

"The polarization of light scattered by sulphur particles is one of the most conclusive reasons for considering it to be an analogue of the blue light of the sky, for the latter shows a polarization of exactly the same kind when examined at right angles to the sun.

"A cloud of small particles of any kind is capable of producing these effects, the essential condition being that the individual particles should be of small dimensions compared with the wave length of light, so that at a given moment the vibration at a given particle may be regarded as having a definite phase. In this case it was shown by my father that the shorter (blue) waves are of necessity more scattered than the longer ones (red); thus the scattered light is bluer than the original. This conclusion can be justified in detail whether we adopt the elastic solid theory or the electromagnetic theory of the nature of light, but it is also deducible from the general theory of dimensions, without entering upon any details of the nature of light beyond its characterization by the wave length.

"An alternative theory which still sometimes shows its head attributes the color of the sky to a blueness of the air, regarded as an absorptive medium. Such blueness is referred to the presence of ozone and appeal is made to the undoubted fact that a sufficiently thick layer of ozone shows a blue color by absorption. This theory gives no account of why the sky light is polarized, or indeed of why there is any light in the clear sky at all. Further, its fundamental postulate that the air is blue by transmission is contrary to observation. The setting sun is seen through a greater thickness of air than the midday sun. According to the theory under discussion, the setting sun ought to be

the bluer of the two, which everyone knows it is not. No doubt the presence of ozone tends to make the air blue by transmission. But this effect is more than compensated by the lateral leaking (scattering) of blue from the beam, which makes the transmitted light yellow.

"If it be conceded that the blue sky is due to scattering by small particles, we are confronted with the question, Of what nature are these particles? At the time of my father's early investigations (1871) this was left open, though they were regarded as extraneous to the air itself. In 1899 he returned to the subject, and considered the matter from the point of view of what was lost by the original beam by lateral leakage (scattering) which simulates the effect of absorption. He then found that the air itself, regarded as an assemblage of small particles (molecules of oxygen and nitrogen) would have an apparent absorbing power not much less than that actually deduced by observations of the sun at different altitudes. The inference was that the air itself was capable of accounting for much, if not all, of the scattering which is observed in the blue sky; in fact, that the molecules of air are the small particles in question."

Lord Rayleigh then proceeded to show that dust-free air does scatter blue light. That the clear blue color of the sky is due to scattering by air particles appears probable from these experiments, but that fine dust in the air also acts powerfully in scattering the shorter waves of light is indicated by the fact that when seen through the volume of fine dust thrown up by the outburst of the volcano of Krakatoa the sun appeared green, orange or red according as it was seen through a greater or less volume of dust. Also when the sun is seen through the dusty air following droughts or through a volume of smoke it is of a deep red color on account of the scattering or absorption of the shorter rays.

Further separation of the light rays is due to diffraction, or the bending of the light rays as they pass the edges of the particles, the blue rays being bent more than the red. When the particles become large, reflection and absorption exceed diffraction.

The colors of the sunset arise from the scattering of the shorter rays as they pass through a great thickness of air. When the sun sets below the horizon its rays are reflected by the dust or cloud particles in the air. When the sky is clear, only the blue rays are lost at first, so that the sky near the horizon has a greenish or yellowish tinge. This deepens into orange and then

into deep red as the sun gets far below the horizon, and the volume of air traversed becomes greater and greater. A second reflection of the sunlight is also a prominent feature of the sunset in clear weather. This reflection appears in the sky opposite the red glow and is known as the twilight arch. After sunset it is a rosy arch spanning the eastern sky above the dark blue shadow of the earth, while before sunrise it is a similar arch in the west. When the sun is far below the horizon the secondary glow is seen on the same side of the sky as the sun, that is, in the west after sunset and in the east before sunrise. This afterglow is brightest about thirty to thirty-five minutes after sunset when the primary color has nearly all disappeared, or the same interval before sunrise. When there is a great quantity of fine dust in the air, as there is after great volcanic eruptions, the afterglow may last for more than an hour after sunset. These afterglows were especially striking over the whole of the northern hemisphere for months after the great explosion of Krakatoa in 1883.

When the dust or cloud particles are large they cease to scatter the light, except by reflection, and appear as haze or cloud. In large masses they reflect the sunlight from their upper surfaces and absorb the light entering them, so that seen from below they appear dark, grayish or black.

When there is a large quantity of condensed vapor in the air to the west of the observer the sun's rays are entirely absorbed and the ordinary colors are absent. It is for this reason that a gray sunset portends rains. On the other hand, unusually clear, pure colors portend fine, cooler weather, while a haze which causes the sun to appear as a blood-red ball even before setting accompanies droughts.

Zodiacal Light.—After all color has faded from the sky, a whitish cone of light is sometimes seen in the western sky, especially in spring and autumn. Careful observation has shown that this glow is outside the atmosphere and is probably due to diffuse reflection from small particles in space between the sun and the earth. It is called the Zodiacal Light and appears as a faint pyramid of light rising above the horizon. It is most easily seen in the evening in spring and in the morning in autumn; because at these times the angle between the plane of the zodiac and the horizon is greatest.

Rainbows.—Next to the sunset colors the rainbow is one of the most striking appearances in the sky. It usually accompanies a shower of rain and is seen as an arc of brilliant colors appar-

ently occupying an immense expanse of the sky opposite to the sun. The bow usually shows six bands of pure color, blending into each other, red, orange, yellow, green, blue and violet, the indigo being generally absent. In the primary bow the violet color is on the inside and the red on the outside. Often two rainbows appear, a primary and a secondary, the secondary being outside the primary with the colors reversed, the red being on the inside of the bow. On occasions there are seen additional bows, along the inner side of the primary and the outer side of the secondary.

The rainbow is caused by the joint action of refraction, reflection and dispersion of the rays of light. A ray of light coming from the sun enters a falling rain drop, is bent slightly toward the center of the drop from the rear surface of which it is reflected and passes out at the lower surface of the drop to the observer's eye. But, in going through the drop, the different wave lengths which give rise to the sensation of color are bent to different degrees, so that they are separated in such a way that the violet, which is deflected most, appears to be below the blue, and this below the green, etc., while the red, which is least bent from its course, is on top. The whole theory of the bow has been the subject of a rigid experimental and mathematical demonstration.

Glories.—Brilliant colored rainbow-like rings, called glories, are sometimes seen surrounding the shadow of an observer's head when he is looking away from the sun toward a bank of fog, or looking down from a balloon or mountain on to the top of a stratum of clouds. Around the shadow of the observer's head is seen an aureola or series of colored rings which are sometimes very brilliant and beautiful. These also are caused by the separation of the light rays into different wave lengths when passing around the droplets of the clouds.

Coronas.—Colored rings seen around the sun or moon when the light from these bodies passes through fleecy clouds are called coronas. The corona, like the rainbow, has the violet on the inside and the red on the outside. The colors, as a rule, are not pure and well defined like those of the rainbow. On account of the diverse sizes of the water drops in the cloud there is an overlapping of the colors and frequently it is only possible to distinguish a reddish color on the outside and a bluish within.

Halos.—When thin cirro-stratus clouds are spread out in advance of a barometric depression, there are sometimes seen bright rings of whitish light surrounding the sun or moon. This ring

is due to the reflection and refraction of the light by the falling ice crystals of which the cloud is formed. These rings are of different sizes, dependent on the manner in which the ice crystals are falling and on their form. In general the ice crystals are hexagons and they fall in such a way that the maximum of refraction is at an angle of about 22° from the sun or moon, so that halos of 22° radius are the most common, although halos of 46° and 90° are sometimes seen. The reflection of the light also, at times, causes vertical beams which cut the arcs of the halo and form magnificent crosses of brilliant white, or form short inverted arcs which cut the circle of the halo. These brilliant figures in the sky assume such a variety of shapes that they have been the cause of a vast deal of superstition in the past and have served as portents of dread evils to be anticipated. The halo is found in the outer edge of the cloud which accompanies a storm or cyclonic system of winds and is frequently a forewarning of coming rain within the next twelve or sixteen hours.

Scintillation.—The unusual twinkling of stars is another phenomenon noticed in advance of the coming storm and gives an indication of the disturbed state of the atmosphere. It is caused by the small ripples or waves set up at the surface of a colder stratum, over which is flowing a current at a higher temperature. Helmholtz has shown that, when a warm current is overflowing another of lower temperature, waves are set up in the colder air mass which have many of the properties of ocean waves. These waves vary greatly in size. First, there are the enormous billows which fill the whole air mass, affecting the barometer and causing pulsations in the winds and rainfall; second, there are the smaller billows which cause the wavy cloud bands; and third, there are the small ripples which give rise to scintillation of the stars where the continued alterations in the density of the air cause the light waves to be shifted from side to side and give the stars the appearance of dancing. This scintillation which is nearly always present in a greater or less degree makes observations of the heavenly bodies with telescopes difficult, so that astronomers have visited all parts of the world to discover in what region it is least objectionable. According to Pickering, it is found to be least within the tropics, and for that reason the Harvard College Observatory has located most of its branches within that region. Exner has shown that the waves which cause scintillation are from 1 to 20 centimeters from crest to crest. Sometimes there are several sets of such waves in the atmosphere at different heights, as was shown by Douglass.

The Aurora.—Of all the phenomena of the skies none is more inspiring than the aurora which illuminates the night skies in the high latitudes of both hemispheres. It appears in the form of dancing beams of light, sometimes white and sometimes of brilliant colors, red, green, or blue, which flame and scintillate and come and go.

By their following the magnetic lines of force and by their effects on the magnetic needle, they are known to be electric discharges in the higher regions of the atmosphere. The Aurora most frequently forms in arches which stretch around the magnetic pole. At other times it forms in long beams extending across the whole sky which, on account of perspective, appear to converge on a point near the zenith.

By means of photographs taken simultaneously from two distant stations against a common background of stars, Störmer,[1] Vegard and Krogness have secured many measurements of the height of the aurora. The upper limits vary from 100 to heights exceeding 500 kilometers (60 to over 300 mi.) above the earth and the lower limit appears to be about 80 kilometers (50 mi.). At these great heights the atmosphere is almost entirely composed of the lightest gases.

Auroras are intimately connected with the appearance of spots on the sun and are believed to be caused by streams of electrified particles, or ions, or electric rays moving outward from the regions of the spots under the pressure of light waves and entering the magnetic field of the earth when the earth is within or near the line of travel of these particles. According to the theory of Birkland and Störmer the aurora arises from the passage through the earth's atmosphere of electric rays either α (positive) or β (negative) electrons.

The Mirage.—A mirage is a change in the appearance of distant objects near the earth's surface in such a way that the objects appear to be separated from the observer by a sheet of water or to be surrounded by water in which the image is reflected and inverted. Hence the name *mirage,* meaning mirrored or reflected.

It is caused by excessive heating of the air near the earth's surface, as a result of which the lowest layers become slightly less dense than those above them. For the best development of this condition a broad flat plain or basin in an arid region and intense solar heating are essential. Similar mirages on a smaller

[1] "Terrestrial Magnetism and Atmospheric Electricity," Vol. 21, pp. 157 and 169, Washington, 1916.

scale are seen over a warm body of water over which a cool wind is blowing or even over a highly heated asphalt pavement. If the ground is moist, evaporation keeps the surface cool; or, if the land is surrounded by cool water, the cooler air flows in and lifts the warmer air, forming a sea breeze. But over arid plains the surface air continues to heat until it is actually lighter than the air above it. Normally the air decreases in density with increasing height above the ground and for the condition to be reversed the temperature must decrease 1° C. (1.8° F.) for each 29.27 meters (about 100 ft.), a decrease of temperature with height 3.52 times faster than the adiabatic rate.

FIG. 183

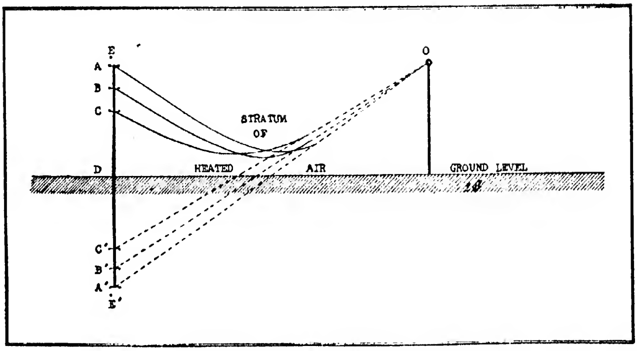


Diagram Illustrating Mirage—After W. H. Steavenson

Where there is no cooler air to upset the equilibrium by lateral pressure this excess of heat accumulates in the lower air making it less dense than the air above it, until mixing begins by the ascent of the lower air, which in a tranquil condition of the air is probably retarded by viscosity.

Observations made by W. H. Steavenson in Egypt[2] indicate that the excess of heating takes place almost entirely in the lowest six feet of air. When the mirage was well developed he observed a difference of 5.9° F. (3.3°C.) between the air within 1 inch of the earth's surface and 5 feet 6 inches (1.6 m.) above. This rate is about 16 times greater than the adiabatic rate.

The rays of light in passing into the less dense air near the

[2] *Quarterly Journal of Royal Meteorological Society,* Vol. 47, p. 15, London, 1921.

surface are bent away from the normal, just as a stick appears to be bent when partly submerged in water. At a certain angle the ray no longer passes into the denser medium, but is reflected back from the boundary of the two media.

An observer whose head is above the heated stratum while seeing a distant object, like a tree or hill by the light which comes from it in straight lines, will also see an inverted image apparently reflected from a pool of water. This effect is illustrated in Fig. 183.

An observer at O sees the object directly, he also sees the object by the curved rays of light CO which appears to come from the direction of $C'O$. He sees in addition the light from the blue sky E which after following a curve appears to come from E' and hence appears to be a sheet of blue water in which the object ABC is reflected. These mirages are seen in all deserts but are especially striking in the regions of high, dry table-lands like those of Bolivia and Peru.

CHAPTER X

THE SUN AND THE WEATHER

SUMMARY

The correlation of weather changes with changes in solar radiation is here brought out. The day-to-day changes in temperature and pressure in all parts of the world are shown to have an intimate relation to short period changes in solar radiation. With an increase of solar radiation, the temperature rises and the pressure falls in equatorial regions and is immediately followed by a rise of pressure and a fall of temperature in temperate regions, reaching a maximum between latitudes 40 and 60 degrees north and south. From the region of maximum rise of pressure, a wave of returning pressure starts towards the equator but also drifts eastward with the eastward drift of the atmosphere. These waves are believed to be the cause of the waves of temperature and pressure described in Chapter IV. Their complexity arises from the complexity of the changes in solar radiation, in which changes of short period are mixed with progressively longer waves of change going up into years and centuries. In this chapter the monthly means of solar radiation are considered and shown to be intimately related to changes in the monthly means of temperature and pressure and it is shown that with an increase of intensity of solar radiation the maxima of pressure form over the coldest parts of the temperate zone, which are the continents in winter and the oceans in summer. The more intense the radiation the farther north are these maxima of pressure formed. The abnormal distributions of temperature and precipitation are intimately related to the distribution of pressure and may be interpreted in the light of the wind systems to be expected from the observed distribution of pressure.

Year-to-year variations in solar radiation are shown to be connected with year-to-year variations in rainfall and river heights in North America, South America and Australia. The observed change of solar radiation in the sunspot period of about eleven years is next considered and long period weather changes are found corresponding to these long period changes in solar radiation. In order to compare the annual solar radiation values and the year-to-year changes in weather condition with the sunspot period, it is necessary to smooth both by getting means of three or four years. The best results are found from overlapping means of four years, which are further smoothed by getting means of each consecutive two. From these smoothed means it is found that the pressure falls in the equatorial regions and rises in higher latitudes in a manner very similar to the results following changes of solar radiation of a few days or those following changes in the mean monthly and mean annual values. The resulting disturbances of temperature are also similar.

Furthermore, the eleven-year changes, both in solar radiation and of atmospheric conditions, are much less marked than the changes of shorter duration.

THE dependence not only of human life but of all life on the light and heat emitted by the sun has so impressed itself on

the mind of man throughout the ages that in every quarter of the globe, from the plains of Syria to the highlands of Peru and from the deserts of Egypt to the icy coasts of northern Europe, religious cults have sprung up based on sun-worship or on an elaborate ceremonial connected with solar changes. Modern science, although divesting itself of earlier superstition, has detracted in no way from the vast importance in human affairs of solar radiation.

The brief absences of the usual warmth and light of the sun during the short intervals of solar eclipses have served to accentuate the importance in mundane affairs of the solar rays.

As the eclipse comes on, a dark chill begins to settle over the face of nature, all animal life becomes restless and uneasy, the lowing of cows, the whining of dogs, the lulled twitter of birds and the unrepressed superstitious fears of the ignorant all tell of our intimate dependence on the life-giving energy of the sun.

Under such conditions one no longer wonders at ancient sun-worship, nor feels it strange that the unenlightened are frightened at seeing the Sun-God extinguished before their eyes.

It no longer excites wonder that the sun was believed to be the all-powerful god of the universe who gave and withheld life according to his pleasure.

The modern scientist does not attribute to the sun the human emotions of love, hate and vengeance; but he believes no less than did the ancients that on the life-giving rays of the sun depend all human activities. The sun acts on us through that transparent shoreless sea of air which we call the atmosphere. At the bottom of this sea of air we live and in its changing conditions which we know as the weather we find our welfare or our discomfort.

To the changing position of the sun in the heavens all human life is adapted and with the surging flames which heave and roar on his surface are entwined much of human weal and woe.

The changes in atmospheric conditions arising from the daily and yearly movements of the earth have been treated in Chapters I and II, but another important way in which the sun influences the atmosphere has been brought to light by recent researches.

METHODS OF MEASURING SOLAR RADIATION

As long ago as 1837, Pouillet endeavored to measure the heat of the sun and invented an instrument called the pyrheliometer

for that purpose. He was followed by Violle, Crova, Chowlson and the Ångströms, all of whom have added to the knowledge of the subject. Kimball is now carrying on extensive observations of this class in the United States, and observations of a similar nature are being made in Europe, Argentina and in other parts of the world. Such observations are necessary for a knowledge of the amount of heat which reaches the earth's surface and of its variations. But the pyrheliometer is incapable of measuring the actual amount of heat which reaches the atmosphere from the sun because of the reflection, scattering and absorption of the solar radiation by the atmosphere itself. This is a variable and complex effect, owing to the fact that every wave length is reflected, scattered or absorbed differently and that there is selective absorption in parts of the spectrum by certain chemical elements, like ozone, water vapor, carbon dioxide, etc., which may vary in amount with the quantity of the substance in the atmosphere.

In order to study the selective absorption and the scattering of light in the atmosphere, S. P. Langley invented the bolometer, a wonderfully sensitive instrument which enabled him to extend the solar spectrum several times its previously known length.

The intensity of the different solar rays within the atmosphere is shown by the full line in Fig. 184, beginning with the shortest ultra violet rays and running to the longest infra-red rays which include any considerable amount of radiant energy. The length of the visible spectrum from violet to red is shown by the light part of the band in Fig. 184 and is also indicated by the space between the vertical dotted lines. The dips or indentations in the full line are due to absorption of the rays by different substances in the air. By taking observations when the sun's rays have passed through different thicknesses of air and eliminating the absorption bands by means of smooth curves, like the broken-line curve in Fig. 184, it is possible to compute the loss of intensity by scattering and to determine the intensity of the light rays outside the atmosphere.

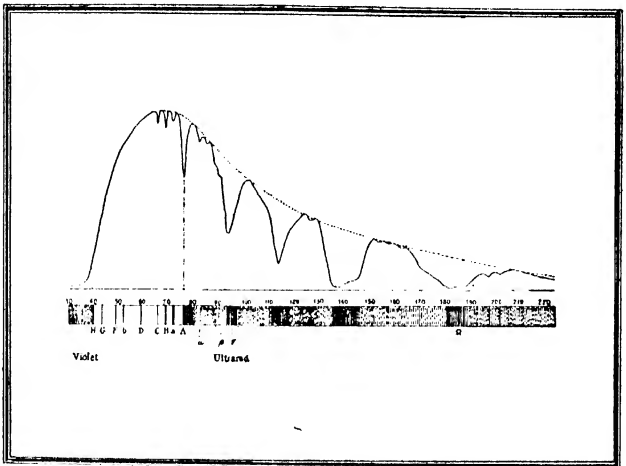
VARIATIONS IN SOLAR RADIATION

As the result of painstaking measurements of solar radiation made during the years 1902, 1903 and 1904, corrected for the influence of the atmosphere, Langley announced that the intensity of solar radiation is subject to irregular variations apparently due to variations in the conditions of the sun itself.

Dr. C. G. Abbot has perfected the apparatus and methods of Langley and by able and persistent work he and his associates have accumulated a long series of measurements of solar radiation in various parts of the world, which not only prove the variability of the sun but promise to be of the utmost importance to meteorology.

Fig. 185 shows a comparison of the measures of atmospheric radiation made simultaneously at Mount Wilson in southern California and at Calama in Chile. This plot furnishes un-

FIG. 184



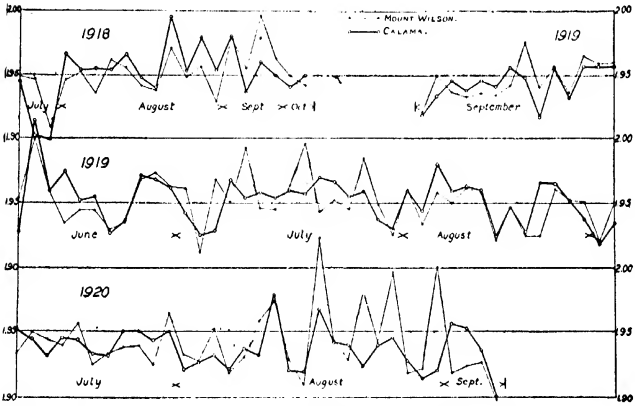
Bolograph and Spectrum Showing Intensity of Solar Radiation for Different Wave Lengths. White Area Shows Visible Part of Spectrum

doubted evidence of solar variability, but there are still outstanding differences between the individual observations owing to the great difficulties of the measurements which, with the highest skill available, are not yet entirely freed from atmospheric influence. The correlations between the individual observations is 0.49, ± 0.050, but when means of five are compared the correlation rises to 0.63, ± 0.065. If overlapping means are considered the correlation is 0.62, ± 0.037. The mathematical analysis indicates a variability of the measurements in California, 14 per cent greater than that at Calama, probably because of unfavorable climatic conditions. The method and meaning of correlation is explained in Appendix B.

Further proof that the observed variations in radiation were

real solar changes was obtained by several independent methods: (1) The contrast between the brightness of the edge and the center of the sun is found by Dr. Abbot[1] to be correlated with changes of solar radiation. In 1913 the correlation was as high as 0.60 ± 0.067. (2) An increase in the intensity of the solar radiation numbers was found to be correlated with an increase in the proportion of short-wave radiation to long-wave radiation. It is well known in physics that the relative proportion of short waves increases as the body becomes hotter. A piece of metal when heated becomes red, next yellowish, then white, and finally

Fig. 185



Simultaneous Observations of Solar Radiation at Mount Wilson, Cal., and Calama, Chile

blue at a very high temperature. (3) There is a correlation between the yearly means of solar radiation and the number of spots on the sun (see Fig. 214). (4) An inverse relation was found by A. F. Moore[2] between the intensity of solar radiation and the intensity of the Fraunhofer lines in the solar spectrum. (5) It will be shown later that there is a correlation between the solar radiation values and the appearance of faculæ on the sun (see Figs. 224, 225 and 226).

Further evidence that solar radiation increases and decreases during a period corresponding with a sunspot period is found in the fact that the polar caps of Mars when turned toward the sun

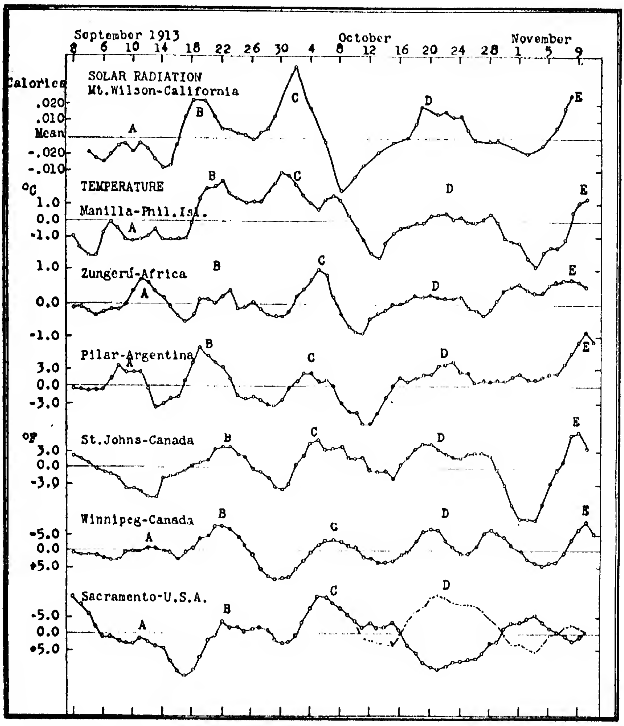
[1] Abbot, C. G.—*Annals of the Astrophysical Observatory of the Smithsonian Institution,* Vol. IV, Chap. VI, Washington, 1922.

[2] *Annals of the Astrophysical Observatory of the Smithsonian Institution,* Vol. IV, p. 186.

diminish in size when sunspots are numerous and grow larger when they are less. Variations in the amount of light reflected by Jupiter have also been found to vary with the sunspot period.

Dr. Abbot believes also that variations in the intensity of the

FIG. 186



Five Day Means of Solar Radiation Compared with Five Day Means of Temperature

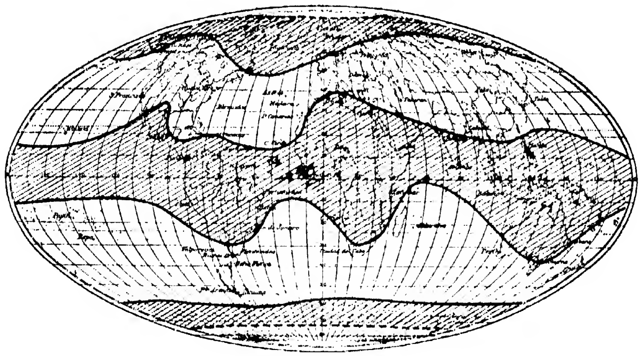
light of Saturn made by Guthnick and Praeger show variations following short period variations in solar radiation.

DAY TO DAY VARIATIONS OF SOLAR RADIATION AND WEATHER

The relation between solar radiation and the weather has been a subject of prolonged research by the author. The first

investigation dealt with the day-to-day values of solar radiation observed by the Smithsonian Astro-physical Observatory in 1913 and 1914 and the changes in the temperature and the pressure in various parts of the world. It was found, that when the solar radiation values are smoothed by getting means of consecutive five days, there is a very evident similarity to the temperature changes in various parts of the world. In making the comparison the annual and daily periods were eliminated and the residuals of temperature were smoothed by means of five in a manner similar to that in which the solar radiation values were

FIG. 187

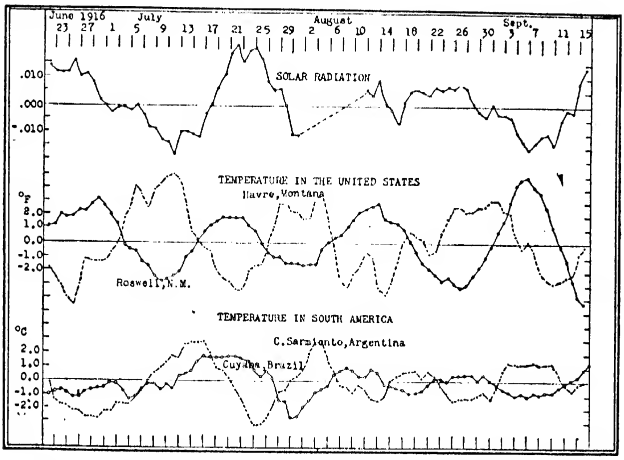


Belts of Direct and Inverse Relations of Solar Radiation and Temperature

treated. The relation is evident by the comparisons shown in Fig. 186, in which the smoothed means of the daily maxima of temperature are plotted for Manila (Philippine Islands), Zungeru (Africa), Pilar (Argentina), St. John's (Canada), Winnipeg (Canada) and Sacramento (United States). At some of these stations the correlation of the temperature with the smoothed radiation values was greater than fifty per cent. At some stations the relation was direct, and at others inverse, as at Winnipeg, where the temperature decreased when the solar radiation increased. At other stations, as at Sacramento, it was partly inverted and partly direct. In a general way it was found that the tendency within the tropics was for the temperature to increase and decrease with the solar radiation, but with a slight lag; while in intermediate latitudes, from 30° to 60° N., there was an inversion, the temperature falling as the solar radiation

increases. In still higher latitudes (60° to 70°) the relation was again direct. It was also found that when the solar radiation increased the pressure fell in the equatorial regions, rose between the 30th and 60th parallel, and fell in the region of 60°–70° N. In other words, with increase of solar radiation the belts of low pressure near the equator and near the 60th parallel are intensified and the belts of high pressure normally near the 30th to 40th parallel are also intensified and displaced toward the poles, so that the atmospheric circulation is increased.

FIG. 188



Ten Day Means of Solar Radiation Compared with Ten Day Means of Temperature in North and South America

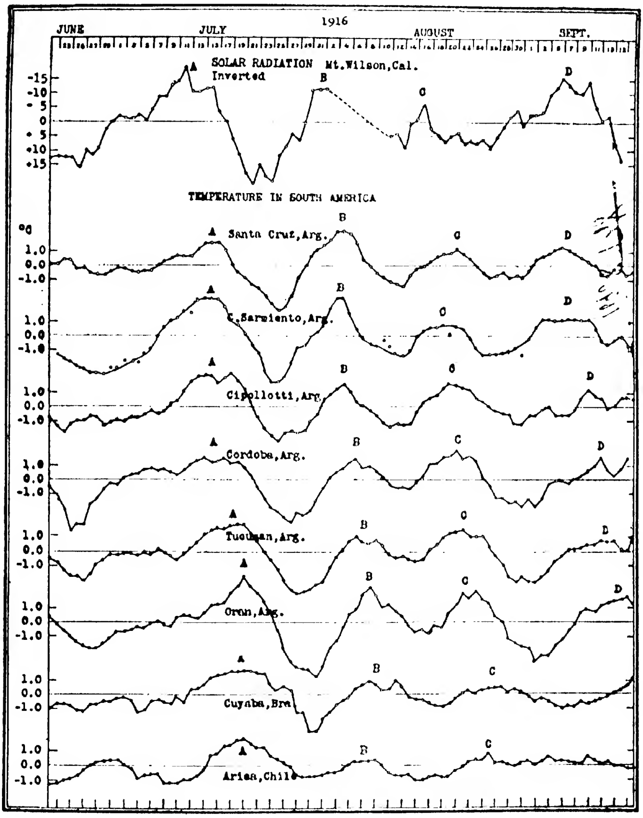
This fact is outlined in Fig. 187. In this figure the shaded areas show the regions within which the temperature increased with increased solar radiation, and the clear regions the areas within which the temperature decreased.

The correlation is less marked when the unsmoothed day-to-day values of radiation are taken, partly because it is not yet possible to make the measurements of solar variation with accuracy and partly because the shorter waves of weather are more difficult to follow.

As the year 1913 was a year of minimum sunspots, it was thought desirable to extend the investigation to a year near a maximum of sunspots and 1916 was selected for the purpose.

For 1916 a comparison was made between ten-day means of solar radiation and ten-day means of temperature and of pressure

FIG. 189



Ten Day Means of Solar Radiation Compared with Ten Day Means of Temperature at Stations in South America

from which the annual and other longer periods were eliminated by subtracting the means of 30 days from the means of 10 days.

The data from four stations are plotted in Fig. 188. One of these, Roswell, New Mexico, in the south of the United States, and another Cuyaba, in central Brazil, evidently tended to

oscillate during June, July and August in the same manner as the solar changes shown at the top of the figure; while stations at high latitudes, as Havre, Montana, in the extreme north of the United States, and Sarmiento, in the south of Argentina, tend to oscillate inversely to the solar radiation.

When, however, curves for adjacent stations in the same country are examined, it is found that the maxima of temperature and pressure occur first in certain regions and from these move outward as shown by the later occurrence in other adjacent regions. *Fig. 189* shows a plot of the ten-day means of solar radiation and of the temperature for six stations in Argentina, for one station in Chile and one in Brazil.[3]

The correlation of the mean solar values with the ten-day means of temperature at the various stations are shown in Table XXI.

TABLE XXI

CORRELATION OF 10-DAY MEANS OF SOLAR RADIATION WITH 10-DAY MEANS OF TEMPERATURE AT STATIONS IN SOUTH AMERICA

Days After	0	1	2	3	4	5	6	7
Santa Cruz	—.44	—.60	—.69	—.74	—.70	—.64	—.49	—.32
Sarmiento	—.60	—.74	—.82	—.81	—.78	—.70	—.55	—.37
Cipolletti	—.26	—.42	—.57	—.68	—.76	—.78	—.70	—.59
Cordoba	—.14	—.29	—.45	—.57	—.66	—.73	—.74	—.72
Oran	+.30	+.14	—.05	—.23	—.40	—.56	—.69	—.77
Cuyaba	+.34	+.28	+.11	+.03	+.15	—.31	—.47	—.59
Rio Janeiro	—.20	—.19	+.05	+.14	+.20	+.24	+.26	+.24

Days After	8	9	10	11	12	13	14	15
SantaCruz	—.12	+.08	+.25	+.40	+.51	+.54	+.52	+.49
Sarmiento	—.19	—.02	+.13	+.24	+.38	+.44	+.47	+.46
Cipolletti	—.45	—.31	—.14	+.01	+.14	+.27	+.38	+.43
Cordoba	—.64	—.53	—.37	—.22	—.07	+.09	+.27	+.37
Oran	—.81	—.78	—.70	—.58	—.42	—.24	—.06	+.17
Cuyaba	—.67	—.76	—.76	—.72	—.67	—.55	—.41	—.23
Rio Janeiro	+.19	+.14	+.11	+.06	+.02	+.01	+.03	+.05

From this table it is evident that the correlation of the solar changes with the temperature in Argentina in midwinter (June to August) is negative; that is, the temperature decreases as the solar radiation increases. In Figs. 189, 190, 191 the mean values

[3] The latitude and longitude of these stations are as follows: Santa Cruz, 50° 11′ S., 68° 21′ W.; Sarmiento, 45° 30′ S., 69° 00′ W.; Cipolletti, 38° 56′ S., 68° 30′ W.; Cordoba, 31° 25′ S., 64° 12′ W.; Tucuman, 26° 50′ S., 65° 11′ W.; Oran, 23° 6′ S., 61° 20′ W.; Cuyaba, 15° 39′ S., 56° 0′ W.; Arica, 18° 28′ S., 70° 20′ W.

of the solar radiation are inverted in the plot to facilitate comparison with the temperature. In computing the correlations the first ten days of August were omitted because there were no solar observations during that interval.

The maximum correlation at Sarmiento for the year 1916 amounts to —0.82, two days after the solar observations. The amount of agreement according to W. H. Dines is in proportion to the square of the correlation coefficient. In accordance with that test 76 per cent of the temperature changes at Sarmiento in winter are caused by solar changes and 23 per cent arise from other causes. But when it is remembered that the solar measurements are not perfect nor complete, it seems that all the abnormal temperature changes after eliminating the daily and annual changes may, and probably do originate from the variations in solar radiation shown by the measurements of the Smithsonian Astro-physical Observatory. In this connection, it is interesting to note that Sarmiento is located in the coldest part of the South American continent in midwinter and it is evidently a center from which these larger waves of temperature radiate, because the maxima and minima of the waves occur later at stations both north and south of that place.

These waves pass northward into southern Brazil and are there superposed on the waves produced by the direct effect of solar radiation, as illustrated at Cuyaba. At that place the direct correlation on the day when the solar radiation was observed is only + 0.34, while nine days later when the inverted waves arrive from the south it is — 0.76. The direct correlation on the same day as the solar changes was + 0.21 in June to July and + 0.40 in August to September, while the inverse correlation nine days later was — 0.89 in June to July and — 0.27 in August to September, showing that the direct correlation increases at that station as summer approaches and the negative correlation due to waves coming from the south decreases. Recent comparisons render it evident that the direct correlation reaches its highest value in summer in both hemispheres in the region where the noon sun is nearly vertically overhead.

Fig. 190 shows a plot of the ten-day means of temperature for Havre, Montana, Devil's Lake, North Dakota, Marquette, Michigan, New York, New York, and Eastport, Maine. This plot shows that the waves of temperature move eastward from Havre just as they move northeastward from Sarmiento. The greatest correlation of temperature with solar radiation is, however, probably at some station to the north of Havre. At Marquette and

New York, the first wave does not appear, perhaps because these stations were too far south, but all are visible at Eastport.

The correlation values for Eastport were as follows:

TABLE XXII

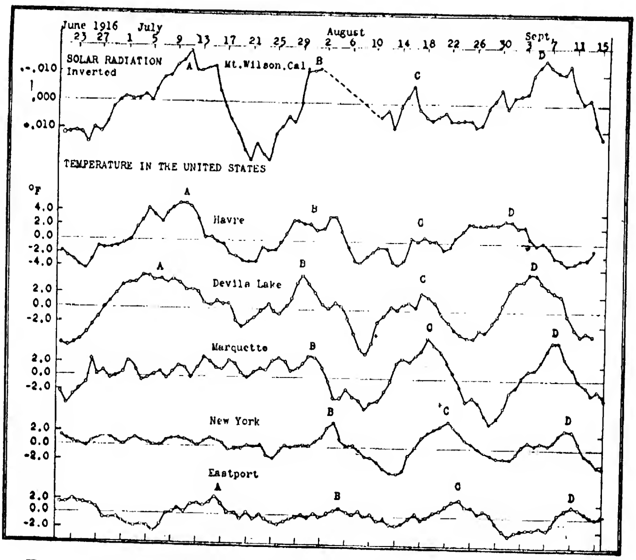
Correlation Between Solar Radiation and 10-Day Means of Temperature

Days after	0	1	2	3	4	5	6	7	8	9
Eastport	+.21	+.06	—0.2	—.01	—.19	—.30	—.34	—38*	—36	—.28

* Minimum.

It is seen from this table that for this class of waves the maxima and minima of Eastport follow those at Havre about seven days in summer.

Fig. 190

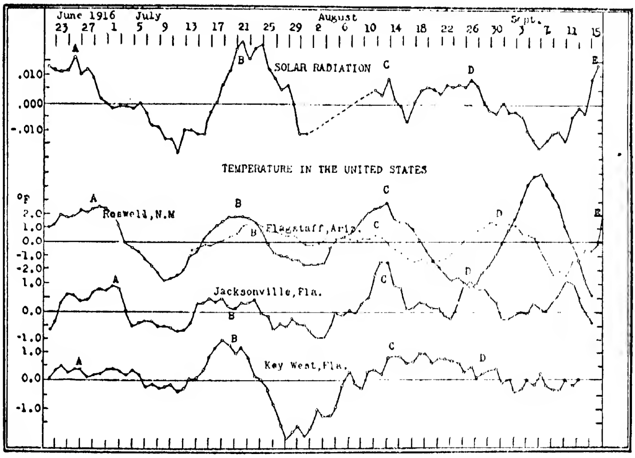


Ten Day Means of Solar Radiation Compared with Ten Day Means of Temperature in the Northern United States

Fig. 191 shows a plot of the temperature waves which varied directly as the solar radiation in the southern part of the United States in the summer of 1916. At Flagstaff, Roswell, Jacksonville and Key West, during a large part of the time covered by the observations, the maxima and minima occurred nearly simultaneously with each other and with the solar maxima and minima.

The correlation of the solar radiation with the temperatures at Roswell and Flagstaff is peculiar in the fact that no correlation is apparent at Flagstaff until July 13 and the correlation changes sign at Roswell after August 15. The correlation for Roswell from June 21 to July 31 is + 0.68 and from August 11 to September 13 is — 0.84, while at Flagstaff two days after the Solar changes the correlation from July 13 to September 15 is — .10 and from August 11 to September 13 is + 0.56. The evidence is,

Fig. 191



Ten Day Means of Solar Radiation Compared with Ten Day Means of Temperature in the Southern United States

that the center of direct relation moves westward and southward with change of season, and in the winter of the northern hemisphere the whole interior of the United States is within the region of inverse correlation to solar changes.

When correlation coefficients are computed for changes of shorter period than those obtained from ten-day means an entirely different relation is found for adjacent stations from the results shown in Fig. 189 and in Table XXI.

By subtracting the five-day means of solar radiation from the observed values and five-day means of temperature from the observed temperatures the residuals show the short period variations. When these residuals of solar radiation and temperature were correlated with each other from the observations of 1916,

the correlation coefficients shown in Table XXIII were obtained for a number of stations in Argentina.

TABLE XXIII

CORRELATION OF SHORT-PERIOD CHANGES OF SOLAR RADIATION AND TEMPERATURE

Days Following Solar Change	0	1	2	3	4	5
Santa Cruz	— .13 *	+ .12	— .09	— .16 *	+ .10	+ .10
Sarmiento	— .30 *	— .10	+ .17	— .12 *	— .04	+ .26
Bariloche	— .08 *	+ .01	— .10	— .17 *	+ .25	+ .10
Cipolletti	+ .07	— .25 *	+ .18	— .20 *	+ .04	+ .26
Cordoba	.00	— .02 *	+ .23	+ .01	— .36 *	+ .15
Buenos Aires	— .13	— .19 *	+ .37	— .07	— .39 *	+ .24
Corrientes	+ .03	— .21 *	+ .12	+ .16	— .13 *	— .16

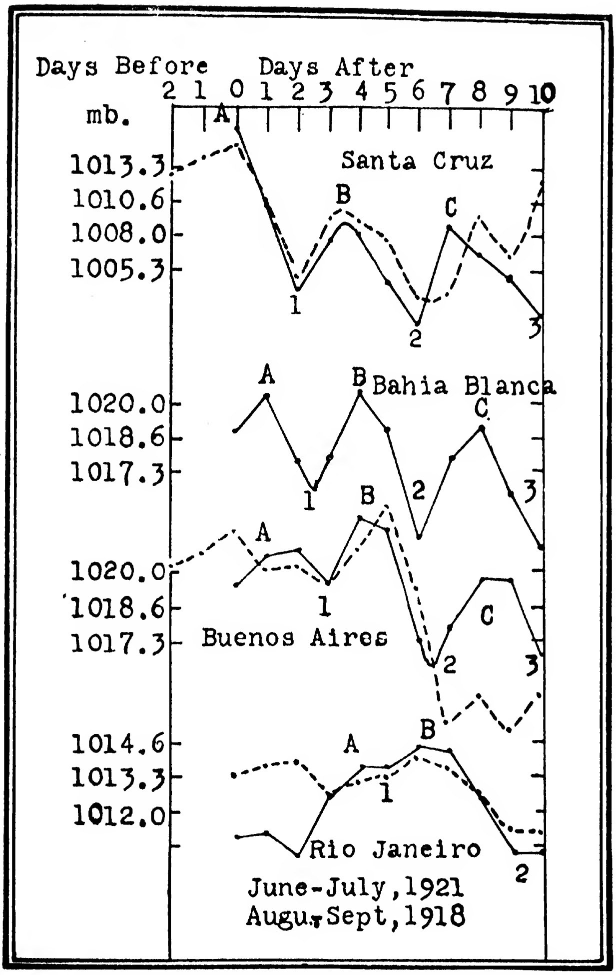
* Greatest negative correlation.

It is seen from this table that the correlation coefficients are small, but a maximum negative correlation of temperature and solar radiation occurs at Sarmiento on the day of the solar observation and at stations farther north on the day after, showing a very rapid progress of the temperature wave. There follows a positive correlation at the southern stations the day after the solar observation and this reaches northern stations one to two days later, that is, it reaches Corrientes on the third day after the solar observation.

How these two classes of waves, shown by the correlations found in Tables XXI and XXIII, combine to produce the results observed at different stations is illustrated by Fig. 192. Selecting all the high values of solar radiation (1.970 and more) observed in August and September, 1918, the mean atmosphere pressure was obtained for a number of Argentine stations for two days before the day of maximum of solar radiation and for ten days following. The same thing was done for the day of maximum radiation and for ten days following the solar maxima in June and July, 1921. When the two sets of values were plotted, it was seen that the pressure sequences accompanying high solar radiation values were very similar at the different stations for the same season of the year.

It is seen that at Santa Cruz a maximum of pressure (*A*) occurs in winter on the day of the solar maximum of radiation and this is followed three and seven days later by other smaller maxima of pressure which are designated *B* and *C*. At Bahia Blanca the maximum of pressure occurs about one day later, but the *A* and *B* maxima are nearly equal. At Buenos Aires the

FIG. 192



Daily Means of Pressure in Argentina Preceding and Following Maxima of Solar Radiation

maxima are one to two days later and the B maximum is larger than the A maximum, so that the chief maximum of pressure occurs four to five days later than the solar maximum. At Rio Janeiro the A maximum is almost merged with the B maximum which occurs six to seven days later than the Solar maximum. The temperature changes are similar to those of pressure but inverse in sign.

These different results are believed to be produced by different classes of changes in solar radiation, resulting in producing a combination of rapid moving and slow moving waves in the earth's atmosphere emanating from the centers of action most affected by solar changes.

For purposes of prediction at any given place the sequences of pressure, temperature and rainfall following different classes of solar changes must be worked out for each month. As time passes this normal sequence will be more accurately determined and better understood.

Systematic observations of solar radiation were begun in Chile by the Smithsonian Astro-physical Observatory in July, 1918, and have been carried on regularly since that time, thus permitting detailed investigations to be made of the relation of solar changes to the weather in all parts of the world for all seasons of the year.

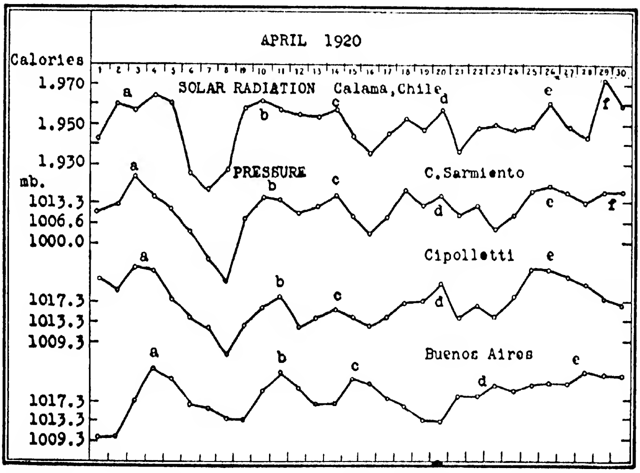
For 50 days from March 26 to May 14, 1920, Mr. A. F. Moore, assisted by L. H. Abbot, performed the remarkable feat of obtaining observations of the solar radiation every day, making the intricate calculations necessary to reduce them and cabling the final result in calories per square centimeter per minute to Buenos Aires.

Fig. 193 shows a plot of the solar values for April, 1920, compared with the changes of pressure at three stations in Argentina. The closest relation is at Sarmiento where the correlation of pressure with the changes of solar radiation is 0.75, $\pm$ 0.06 without any smoothing and without any appreciable lag, or at least not more than a few hours. From Sarmiento the waves moved northeastward, reaching Buenos Aires from one to two days later.

Fig. 194 gives a series of four charts illustrating the formation and the movements of pressure waves in Argentina following the maxima of solar radiation in April and May, 1921. The charts were formed by getting the mean pressure at about twenty-five stations in Argentina and three in Brazil for the same day and for successive days following the maximum of solar radiation up to ten days later, then getting the mean of the ten days and

determining the deviations of the individual days from the mean. In this way the normal distribution of pressure and the long-period changes were eliminated, so that the immediate changes following the solar maxima could be followed. It is seen that a low pressure forms in southern Brazil and a high pressure in southern Argentina on the day of the solar maximum. Both areas move rapidly northeastward and the high pressure in southern Argentina is followed one day later by a wave of low pressure which reaches central Argentina three to four days after

FIG. 193



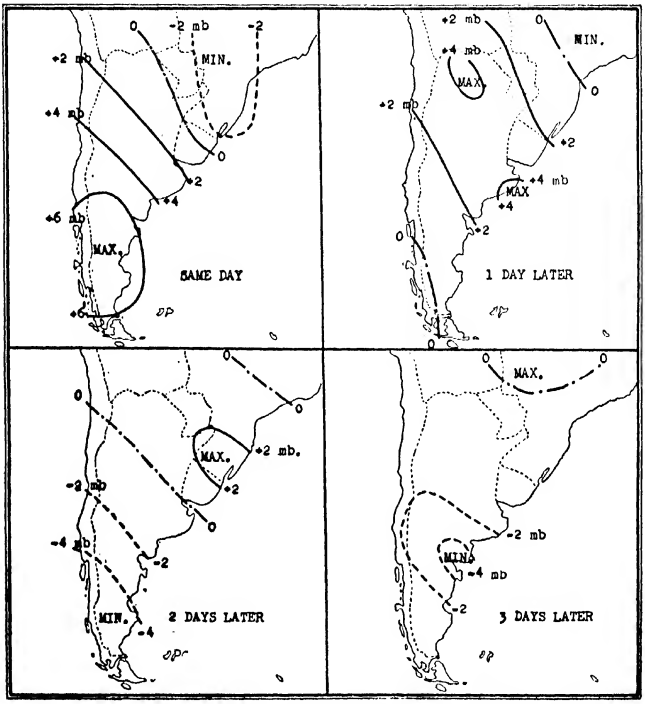
Observed Values of Solar Radiation in April, 1920, Compared with Observed Values of Pressure in Argentina

the solar maxima, causing a maximum of temperature in that region, followed by rain and falling temperature. In the Argentine summer a low pressure caused by the increased solar activity forms over northwestern Argentina, while a high pressure apparently forms over the cool waters of the Pacific to the west of southern Argentina. In winter the high pressure forms over the coldest part of the continent and usually the whole of Argentina is within the region of higher pressure and lower temperature.

The seasonal change in the sequences of the temperature in the city of Buenos Aires following solar maxima is illustrated in Fig. 195. These means were derived from the temperatures fol-

lowing all the solar maxima of 1.970 or more. Here it is seen that the first maximum of pressure in summer passes very quickly with but a slight fall of temperature on the day following. This maximum of pressure is immediately followed by a steady rise of temperature until the morning of the fourth day following

Fig. 194



Progress of Pressure Waves Following Maxima of Solar Radiation in April and May, 1921

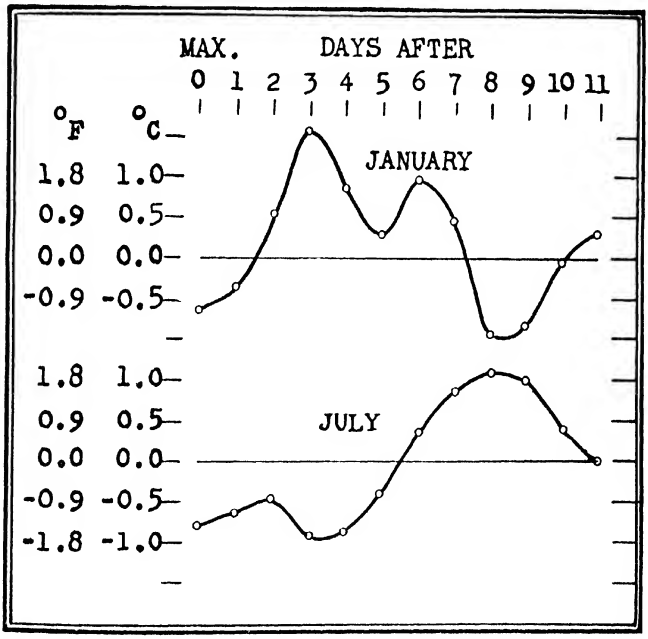
the solar maximum, when a fall of temperature sets in and a minimum is reached on the eighth to ninth day. In winter the relation is nearly the reverse of that in summer. A minimum temperature is reached three to four days after the maximum of solar radiation and afterward the temperature rises until the eighth or ninth day following the solar maximum. At times there appears to be a gradual displacement of the winter type to the

summer type, but the data are not yet sufficient to permit this to be determined with certainty. Individual cases vary from the general type and further researches are necessary to unravel the causes acting in producing variations.

MONTHLY MEAN VALUES OF SOLAR RADIATION AND WEATHER

Not only the day-to-day values but also the monthly means of solar radiation computed from the daily observations at

FIG. 195



Mean Daily Temperatures Following Maxima of Solar Radiation in January and July

Calama show considerable fluctuations, as is seen from the plot of the mean values in Fig. 196.

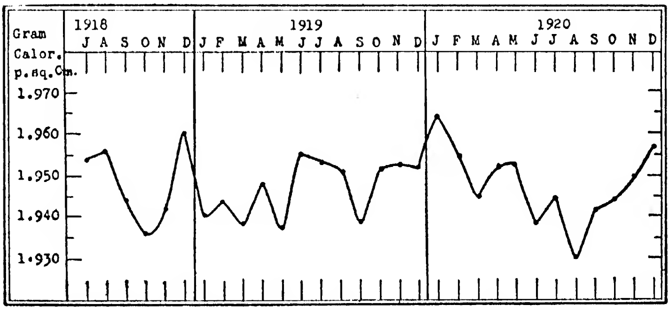
The values for January, 1920, were especially high, and as the month of January is one of the extreme months of the year an opportunity was furnished to study the effect of an increase of solar radiation on the weather of the world at that season.

In the heavy task of collecting and reducing the meteorological data I was aided by William Hoxmark, and the diagrams and charts here presented are taken from our paper containing the detailed observations presented to the Chief of the Argentine Weather Service, January, 1922, and published in the *"Boletín mensual de la Oficina Meteorológica Nacional,"* Buenos Aires, 1919.

For determining the solar influence two sets of comparisons were made: (1) The pressure, temperature and rainfall of January, 1920, were compared with that of 1919. (2) The pressure, temperature and rainfall of January, 1920, were compared with the normal.

The mean value of solar radiation for January, 1919, was 1.940 gram calories per square centimeter, which was almost exactly

FIG. 196



Mean Monthly Values of Solar Radiation at Calama, Chile

the same as the mean of all the values for the three years 1918 to 1920. The mean for January, 1920, according to the latest corrections, was 1.964, or about 1 per cent above 1919 and about 1.4 per cent above normal. The effect on the weather of this increased solar radiation was studied by subtracting the means of the observed values of the elements at each station in 1919 from the mean of the observed values in 1920.

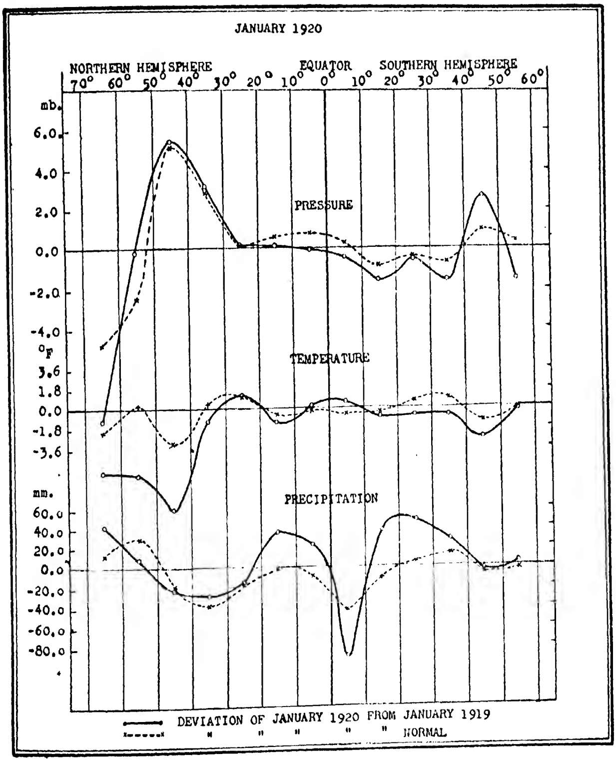
These means were derived from a network of stations scattered all over the world where observations could be obtained. The differences were then plotted on maps and also were averaged for each zone of 10° latitude.

The positions of the stations from which data could be obtained are shown in Fig. 198. The averages for the zones of 10° of latitude are shown in Fig. 197.

In this figure the continuous lines show the departures of 1920 from 1919 and the dotted lines show the departures of the observations of 1920 from the normal.

The two sets of curves run remarkably alike. There is found a deficiency of pressure in the part of the earth directly under the

Fig. 197



Zonal Effect of Solar Radiation in January, 1920

sun, that is between the equator and 30° S. and an excess of pressure between 40° and 50° N. and S. and especially in the northern zone, but between the 60th and 70th degrees of latitude there is a marked deficiency. These facts clearly indicate an increase in the normal atmospheric circulation with increased radiation.

The effect of the increased solar radiation on the temperature

was not so marked as on the pressure. In the part of the world from 20° N. to 20° S. and from 40° to 60° N. and S., which embraces the larger part of the whole world, the surface temperature was, in general, lower at the time of the greatest solar radiation, a fact which is clearly seen when comparing the departures of 1920 from 1919. At higher latitudes the temperature increases with increased solar radiation.

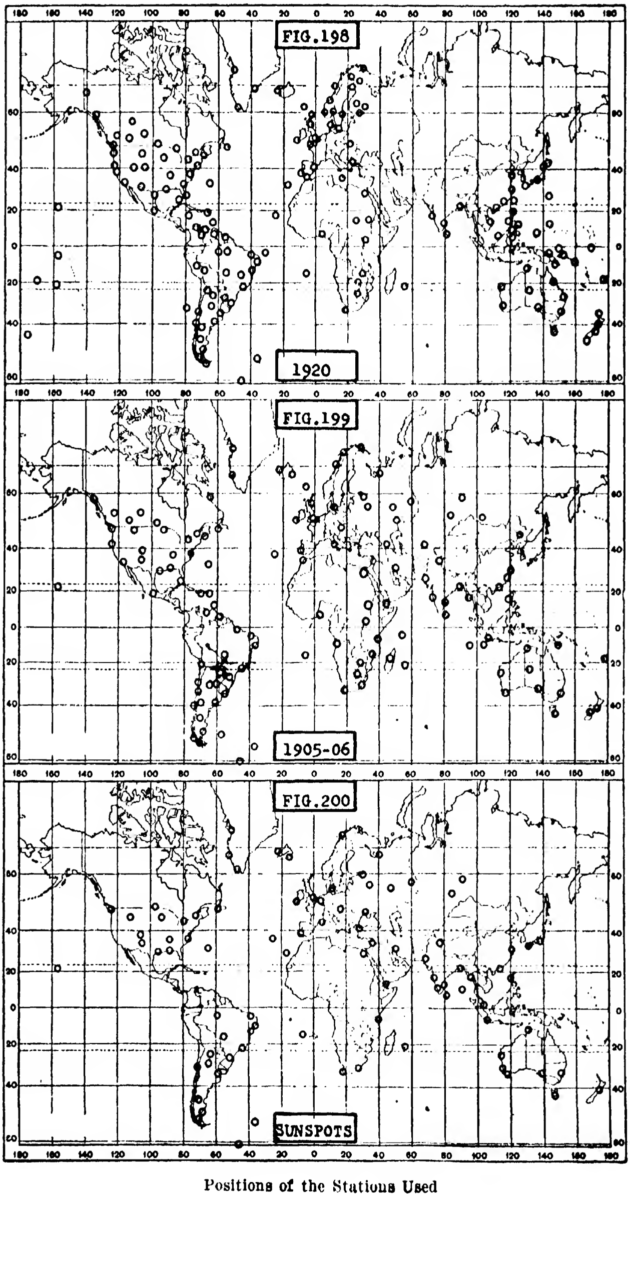
The effect on the rainfall is more difficult to determine with accuracy, on account of the local conditions which influence rainfall, but, on the whole, there was an increase of rainfall in the low-pressure belts between latitudes 60° and 70°, a decreased rainfall in the high-pressure belts between 30° and 50° latitude N. and S. and an excess of rainfall in the tropics except in the zone between latitudes 0° and 10° S. The excess of rainfall was especially marked between 10° and 30° S., which is the belt directly beneath the sun in January.

Because February, 1920, also showed a high mean value of the solar radiation, although less marked than in January, it seemed worth while to extend the investigations to include that month also.

The data were plotted on maps of the world. Fig. 198 shows the position of the stations and Fig. 201 shows the lines of equal departures of pressure, temperature and rainfall of January, 1920, from those of January, 1919. The lines of equal pressure departure are drawn for each 4 millibars (3 millimeters), except near the equator, where they are for each 2 millibars; the lines of temperature departure are for two, four, and ten degrees Centigrade (3.6°, 9° and 18° F.), the lines of rainfall departure for each 50 millimeters (2 inches). The areas of excess are shaded, while the areas of deficiency are left blank.

A distressing feature of the maps is the absence of data from large areas like Russia and Siberia, the south Pacific and the polar regions; but the data are sufficient to indicate clearly the laws governing the changes. These areas of deficient data are left in blank and indicated by the words "no data." The upper chart in Fig. 201 shows the distribution of the pressure departures.

There was a deficiency in pressure over nearly the whole of the tropical zone south of the equator. Only in eastern South America was there a slight excess, probably due to an increase in the high pressure about 30° S. in mid-Atlantic. The air from the southern tropics evidently overflowed on to the cold continents of the north, causing a marked excess of pressure, espe-



Positions of the Stations Used

cially in western Canada where the excess exceeds 20 millibars. An excess is also found over southern Europe and undoubtedly there was a more marked excess over Siberia. There was also a slight excess over northern Africa and near 40° S. over Argentina and southern Australia.

On the other hand, the pressure fell over the warm waters of the northern hemisphere. A marked deficiency was found over the north Atlantic and a similar deficiency probably existed over the north Pacific. The pressure was below that of 1919 at Honolulu and at stations along the coast of Japan.

The distribution of temperature shown in the central chart in Fig. 201 was closely related to that of pressure. There was a marked deficiency of temperature in Canada and the northern United States, in northern Africa and in southern Asia, probably resulting from an excess of northerly and northwesterly winds aided by active radiation from the land surfaces in the clear air of the anticyclone, while in the southern United States and Mexico there was a slight excess of temperature. This excess and the excess of precipitation which accompanied it in the southern United States no doubt arose from the excess of easterly winds called for by the abnormal distribution of pressure.

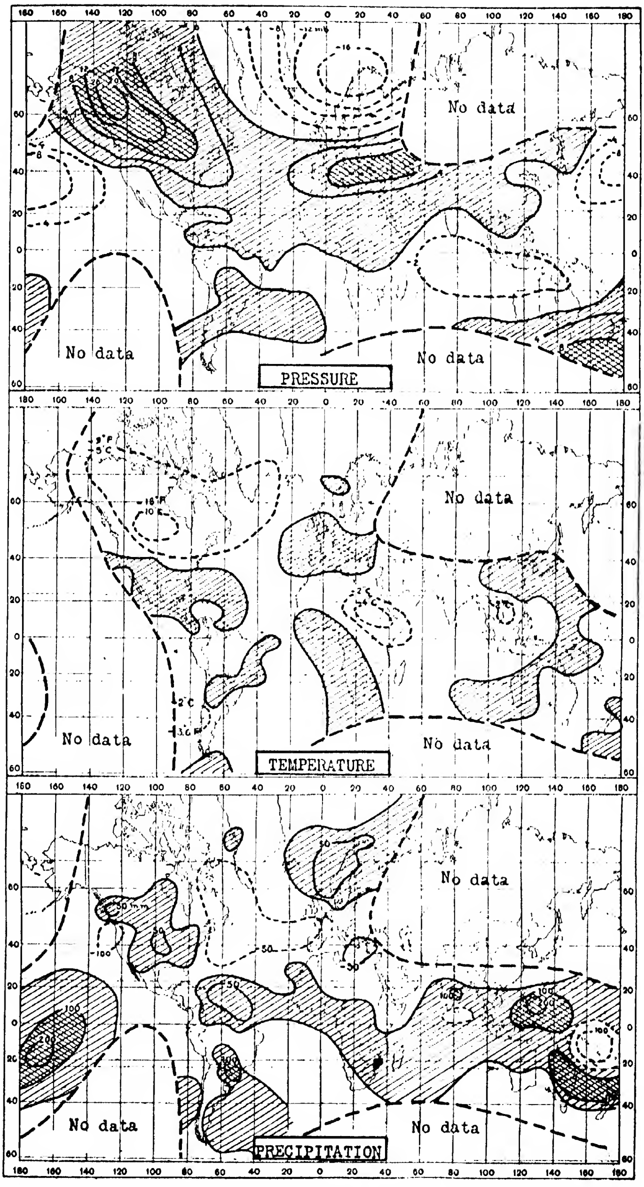
The distribution of pressure also indicates an excess of westerly winds from the ocean in eastern Europe where the month was milder in 1920 than in 1919, and attended by an excess of rainfall. There was a marked deficiency of temperature on the coast of Chile and over southeastern Australia, no doubt caused by cool winds from the adjacent ocean which is much colder than the land at that season.

In general, as shown by the lowest chart in Fig. 201 there was an excess of rainfall in the tropics which amounted to more than 200 millimeters at some stations. There was a deficiency in eastern Brazil and in the region between 150° E. and 180° E. and 0° and 20° S.

Fig. 202 shows the departures from the normal of pressure temperature and precipitation of January, 1920. The distribution of the excess and deficiencies is seen to be much the same as those found in comparing 1920 and 1919.

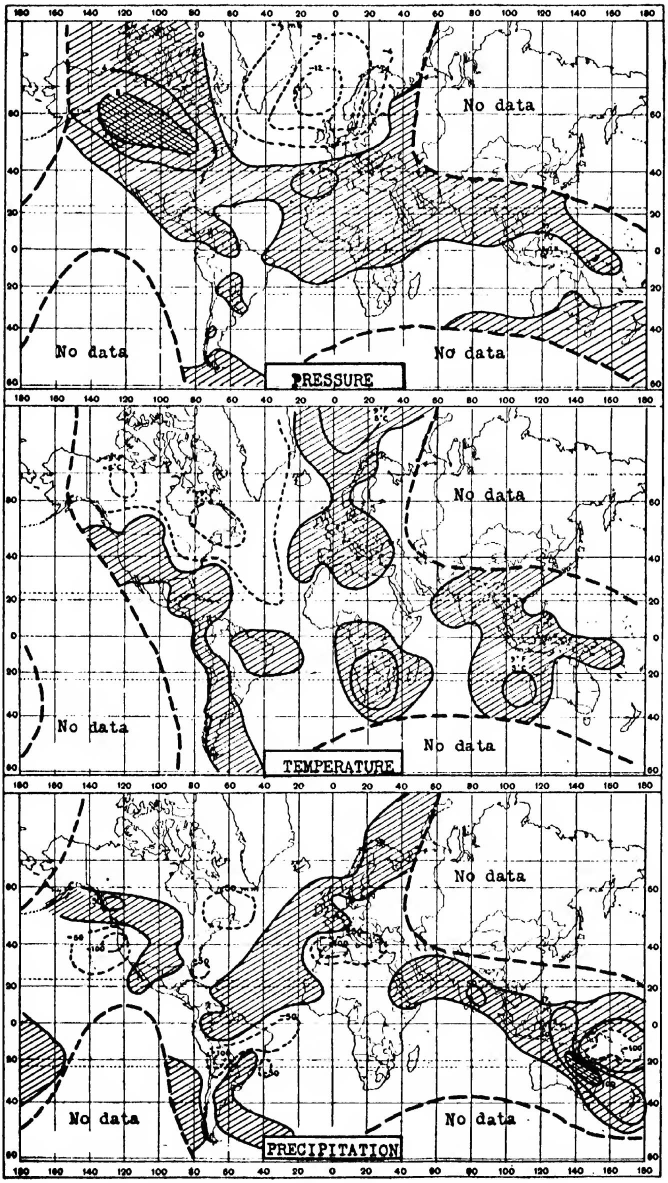
As a result of the increased radiation there was a deficiency of pressure and an excess of temperature in the Argentine provinces, while in the southern territories the pressure was somewhat above normal, especially in the far south. The rainfall was generally below normal in western Argentina and above in the east.

FIG. 201



Departures of the Pressure, Temperature and Precipitation of January, 1920, from that of January, 1919

Fig. 202



Deviation of January, 1920, from Normal

The coast of Chile was cold and the rainfall somewhat above normal.

In Brazil the pressure was above normal north of the equator and mostly below normal to the south. The temperature showed an excess on the east coast, but was deficient in the interior. The weather conditions in other parts of the world can be followed from extracts taken from the reports of the various weather services of the world and from other sources as follows: The reports from official sources in Europe state that there was much storminess and exceptionally heavy rainfall in western and central Europe. Paris suffered considerable damage from floods. The Seine at Port Royal reached a level of 24 feet, 3 inches above the normal, the highest ever reported. In Paris and suburbs 22,000 persons were rendered idle on account of flooded factories. Flood waters in the Rhine and Moselle rivers reached the highest stage in 136 years, according to official German reports. Heavy floods were also experienced in the rivers of Bohemia and Moravia, and on the 17th and 18th the Danube inundated the lower streets of Budapest.

In the British Isles the weather was mild and stormy. In some parts of England the temperature exceeded the January normal by 4° F. Comparatively high temperatures extended as far as the Arctic Circle, the thermometer at Spitzbergen standing at about 36° F. for a few days.

Heavy rains fell throughout most of Italy. The Arno and the Tiber overflowed their banks and inundated many sections.

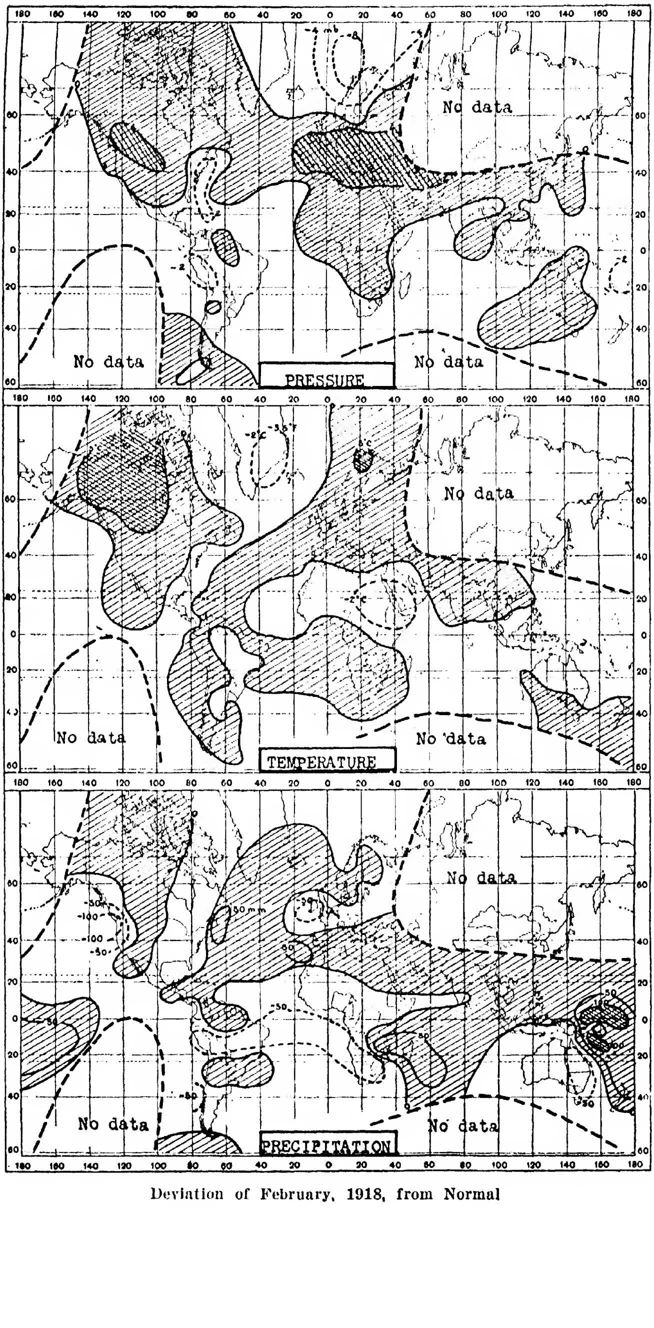
Exceptionally cold weather was experienced in Russia, Turkey and Palestine. The worst winter ever recorded was reported from Palestine and the whole region to the east of the Mediterranean. In Jerusalem there was a fall of 39 inches of snow in early February (the greatest since 1860). Communication between Jerusalem and Cairo was interrupted for a week.

In the northeastern United States, Canada and Nova Scotia the winter was the coldest for many years. A report from Halifax says: "The solid ice extends further south than at any time within years, with the bays and inlets fringing the Newfoundland coast locked tightly." Newfoundland railways were completely tied up and communication between settlements was impossible except by dog sleds.

In Fig. 203 are found the departures of pressure temperature and rainfall of February, 1920, from the normal of February.

There is seen to be, in general, a similar distribution of the excesses and deficiencies as existed in January. There is a

Fig. 203

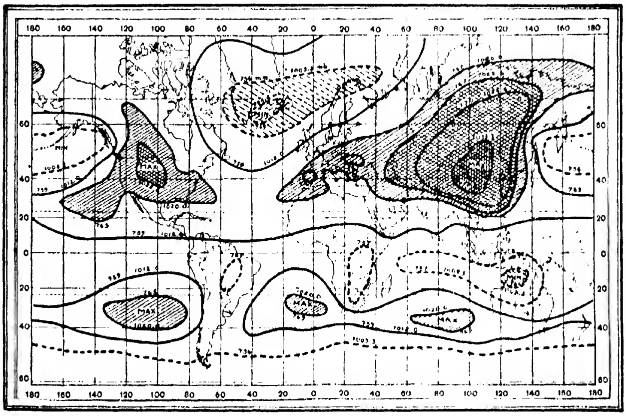


Deviation of February, 1918, from Normal

deficiency of pressure in the equatorial region and an excess over the land surface of the north between the 30th and 60th parallels of latitude, with a deficiency over the northern oceans, but the departures are less marked than in January, as was to be expected from the diminished solar radiation.

Another feature of great interest and importance is the displacement of the centers of greatest excess and deficiency. The center of greatest excess in North America has moved southward from northern Canada to the northwest part of the United States

FIG. 204



Normal Distribution of Pressure for January After Buchan. Shaded areas indicate pressure above normal.

and the deficiency of pressure near Iceland in the north Atlantic has moved northeastward toward Spitzbergen. The deficiency of temperature in Canada has moved eastward to the coast of the United States and the western north Atlantic Ocean and a warm wave has appeared in the northwest of the United States and Canada. The excess of temperature in western Europe has increased and extended eastward as far as Finland. The excessive rains of eastern Australia in January have moved eastward to the islands of the western Pacific. This progressive movement of the centers of disturbance following solar changes is a matter to be taken into account by investigators of solar phenomena.

Fig. 204 shows the normal distribution of pressure for January over the world, and it is seen that the regions of high and low

pressure are, in general, the same as those where there is an excess and deficiency in January, 1920, except that the centers of excess and deficiency in high latitudes are somewhat nearer the poles.

This circumstance indicates that the effect of an increase of solar radiation is to intensify the normal distribution of pressure and at the same time to displace the centers of high and low pressure in high latitudes toward the poles. The whole atmospheric circulation is intensified, bringing about in temperate and high latitudes a deficiency of temperature and rainfall in those regions where the distribution of pressure calls for a prevalence of winds with a component of motion from the pole, and an excess of temperature and rainfall where winds should prevail with a component of motion from the equator.

Within the tropics the effect of the increased air circulation is to decrease the surface temperature and increase the rainfall.

For the study of the influence of variations of solar radiation on the weather of July a much larger mass of data of solar radiation are available. During the earlier years of observation of solar radiation the measurements were mostly made at Mount Wilson and were confined to the summer and early autumn of the northern hemisphere.

Table XXIV gives the mean monthly values obtained from the latest published and corrected data [4] in which each day's observation is given the same weight. If the observations were weighted the means would be somewhat different.

MEANS OF SOLAR RADIATION, ETC.

The table shows that the highest mean values of solar radiation for July are found in the years 1905, 1906 and 1917. For purposes of study, data were gathered from all available sources for those years. The data were taken from published reports of the various weather services supplemented by reports from meteorological observatories and other sources.

For the southern hemisphere, data supplied by R. C. Mossmann were of great assistance in the preparation of the charts.

The positions of the stations from which data were available in 1905 and 1906 are given in Fig. 199. For 1917 the number of stations was larger and, in so far as possible, the stations were the same as those used in the *Reseau Mondial*.

The deviations from the normals of the monthly means of pressure, temperature and rainfall for each of the months, July,

[4] Checked by Dr. C. G. Abbot, April, 1923.

TABLE XXIV

MONTHLY AND ANNUAL MEANS OF THE OBSERVED VALUES OF SOLAR RADIATION

	1905		1906		1907		1908		1909		1910		1911		1912		1913	
	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days
January ..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
February	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
March ...	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
April	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
May	..	..	47	6	..	..	34	9	..	..	16	10	..	..	42	16	..	..
June	68	9	40	12	..	..	44	20	30	22	33	22	45	16	30	23	..	..
July	72	11	62	11	..	..	35	20	11	23	13	13	17	16	50	20	28	3
August ...	55	13	43	13	..	..	51	29	26	19	12	23	29	27	57	27	40	19
September	30	11	48	10	..	..	38	12	8	14	15	21	38	18	62	4	18	25
October ..	28	9	18	10	..	..	51	17	11	16	27	17	15	22	..	..	-34	25
November	..	..	..	..	..	..	61	7	33	2	27	5	3	13	..	..	-34	5
December	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Year	51	53	43	62	..	..	45	114	14	96	20	111	26	112	46	90	03	78

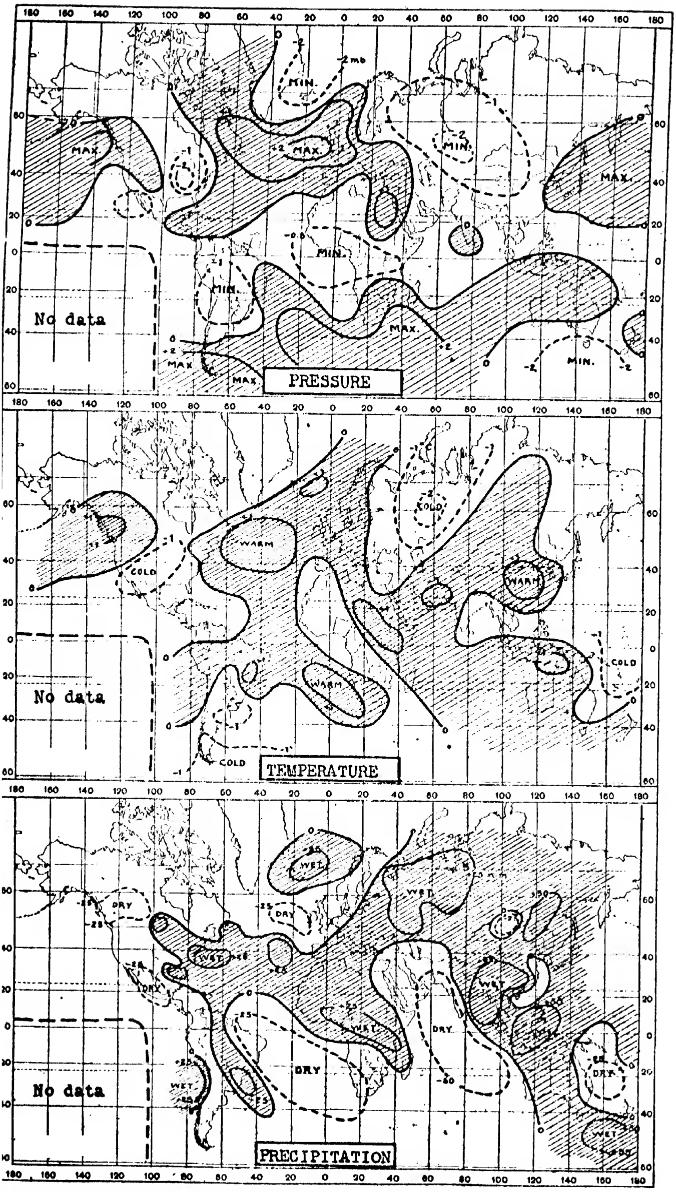
	1914		1915		1916		1917		1918		1919		1920		1921		1922	
	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days	Mean	No. Days
January .	..	..	..	..	..	..	..	..	..	..	43	19	64	25	58	20	45	24
February	..	..	..	..	..	..	..	..	..	..	49	20	56	19	51	21	46	19
March ..	..	..	..	..	..	..	..	..	..	..	41	16	46	29	46	18	34	23
April ...	..	..	..	..	..	..	..	..	..	..	51	27	52	30	47	26	27	26
May	..	..	..	..	..	..	..	..	..	..	40	27	53	29	49	24	27	28
June	54	14	42	14	49	9	..	..	43	5	55	22	39	23	34	24	17	26
July	59	14	47	22	47	25	89	12	54	16	54	27	45	21	45	27	11	23
August ..	66	24	51	27	52	19	56	22	54	27	53	30	30	27	36	11	17	18
September	45	21	68	19	42	21	48	22	44	18	39	28	42	25	44	28	11	18
October .	51	13	50	21	37	11	52	7	34	24	52	20	43	27	47	27	..	..
November	..	..	..	..	..	..	..	..	41	23	53	25	49	25	54	25	..	..
December	..	..	..	..	..	..	..	..	59	19	52	24	55	23	51	16	..	..
Year	56	86	52	103	46	85	59	63	46	116	48	285	48	303	47	267	19	205

Note.—Add 1.900 to columns headed means; so that reading for June, 1905, for example, becomes 1.968 calories per sq. cm. per min. Preceding July, 1918, the monthly means are from observations made at Mount Wilson, California; beginning with July, 1918, they are from observations at Calama, Chile.

1905, 1906 and 1917, were plotted on maps of the world and lines of equal departure were drawn. Because the variations of pressure are less in the tropics than in higher latitudes, the lines of equal values were drawn for less intervals in the tropics than in higher latitudes. The results are shown in Figs. 205, 206 and 207.

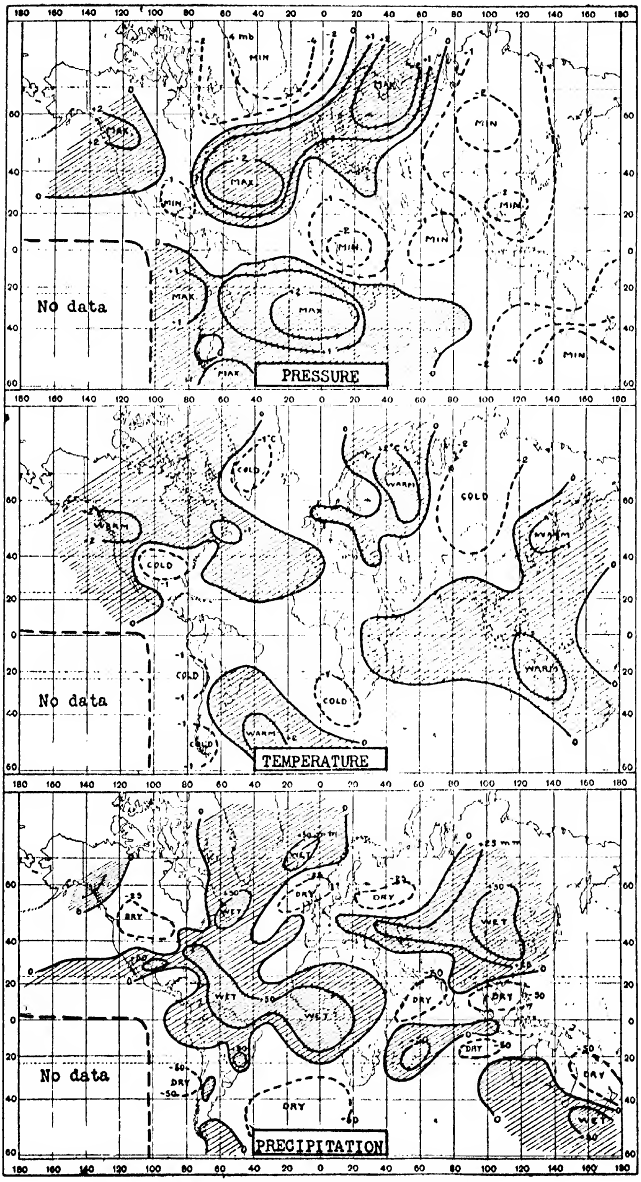
The striking results shown by these charts are that with increased solar radiation in July, the pressure falls below normal (1) in the equatorial region and especially in the humid regions of southern Asia, equatorial Africa and equatorial South America, (2) over the great land areas of central Asia and the central United States and Canada and (3) over the region to the south of Australia and to the north of Iceland.

FIG. 205



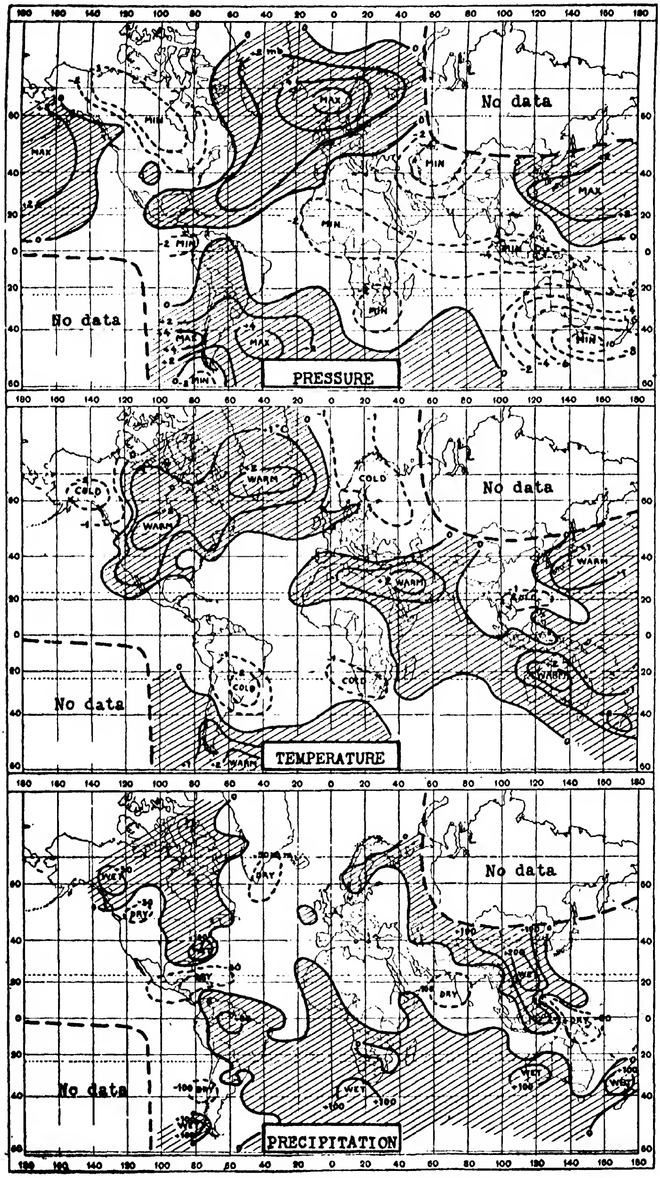
Departures from the Normal of the Pressure, Temperature and Precipitation in July, 1905

FIG. 206



Deviation of July, 1906, from Normal

Fig. 207



Deviation of July, 1917, from Normal

From these regions of deficient pressure the air in the higher strata of the atmosphere probably flows off to the colder waters of the Atlantic and Pacific oceans where the pressure is in excess during each of the Julys when solar radiation was above normal. A most interesting and important fact to be noted, however, is that the excess of pressure is not over the regions where the centers of maximum pressure are usually found over the oceans in about latitudes 30° to 35°, but to the north of those latitudes in the northern hemisphere and to the south of those latitudes in the southern hemisphere. Moreover, the more intense the solar radiation, the further north and south is found the excess of pressure. In 1906 the center of the excess of pressure over the north Atlantic is found in about latitude 38°, in 1905 with somewhat greater solar radiation the center of the excess of pressure is found in latitude 50°, and in 1917 with a high maximum of radiation it is found at 62° N. The same sort of shift took place in the center of deficient pressure over the central United States and Canada. In 1906 the center of deficiency is found in the southern states, in 1905 it is found in the Lake region, and in 1917 it is found in central Canada. Also the maximum excess and deficiency increased with the increase of intensity of solar radiation. In 1906 the excess is + 2.0 millibars in the Azores, in 1905 it is + 2.8 millibars at Kew, and in 1917 it is + 6.5 millibars at Torshaven. In the United States the deficiency in 1906 is — 1.4 millibars at Mobile, in 1905 it is — 2.1 millibars at stations in northern Missouri and Iowa, and in 1917 it is — 3.7 millibars at Prince Albert, Canada, and — 9.5 at Dawson. Evidently similar displacements of the centers took place over Siberia and the southern hemisphere, but the data are insufficient to permit their being followed in detail.

Turning to the charts showing the temperature of the air near the earth's surface, it is seen that the temperatures are low on the polar and on the western sides of the areas of deficient pressure, probably due to an excess of polar winds; while temperatures above normal are found on the equatorial and eastern side of these areas. Also, it is seen that, in general, the surface temperatures in high latitudes in the northern hemisphere are above normal in July within areas of high pressure, and below normal in such areas in the southern hemisphere where winter prevails.

The areas of excessive rainfall are, in general, within and to the east of areas of deficient pressure and between the areas of cold and warm outlined by the regions of defect and excess of

temperature. The areas of deficient rainfall are within the belts of excess of pressure.

Turning next to the years in which solar radiation was below normal, it is seen from Table XXIV that the values of solar radiation were low during the years 1909, 1910 and 1911.

For the years 1910 and 1911 a rich store of conveniently arranged data is found in the *Reseau Mondial* compiled by the British Meteorological Office. The departures from normal given in these reports were plotted on charts and lines were drawn in the same manner as for the preceding years.

The positions of the maxima and minima of pressure are almost the reverse of those in 1905 and 1906. In both 1910 and 1911 there is an excess of pressure in the tropics. There is a deficiency of pressure over the north Atlantic between the 30th and 50th degree of latitude, while there is an excess of pressure over central Siberia and the central United States.

There is a deficiency of pressure over western Australia and an excess in the region of Tasmania.

Taking the mean solar radiation value of the last fifteen years, 1.938 calories per square centimeter per minute, as the normal value, the departures from normal are as shown in Table XXV.

TABLE XXV

MEAN SOLAR RADIATION OF JULY AND DEPARTURES FROM NORMAL

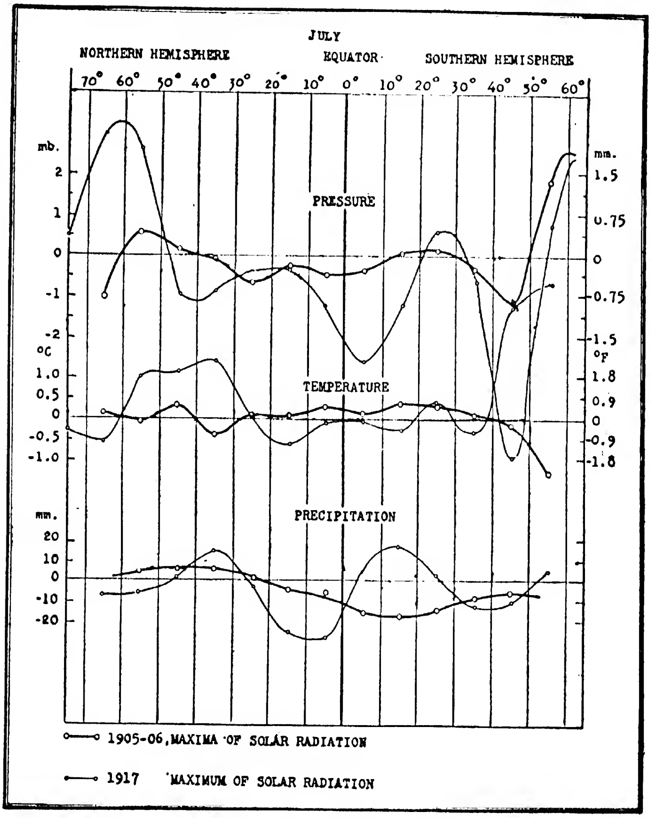
Year	1905	1906	1910	1911	1917
Solar radiation	1.972	1.962	1.913	1.917	1.989
Departures from normal	+ .034	+ .024	— .025	— .021	+ .051

According to these values the solar radiation in 1910 and 1911 was almost as much below normal as the values of 1905 and 1906 were above, while the departure for 1917 was much greater.

In order to study the zonal distribution of pressure the pressure was averaged for each ten degrees of latitude for each of the years. However, one difficulty was encountered in the fact that most of the observing stations are over large land surfaces of the globe and very few are within the ocean areas. In some years the pressure for the whole globe appears to average below normal and in other years above. This anomaly probably arises because the counteracting influence of stations over the ocean and in the polar regions are lacking; but, as the distribution of the stations was more or less the same for all the years, a comparison by zones seems of interest. The departures from normal

for 1905 and 1906 were averaged together, while the anormals of 1917 were averaged separately. The results are plotted in Fig. 208. The conditions for 1905–1906 are shown by the heavy lines, those for 1917 by the light lines.

Fig. 208



Average by Zones of 10° Latitude of the Pressure, Temperature and Precipitation in July, 1905-1906 and 1917

In the curves for 1905–1906 a minimum is found in latitude 60°–70° N., a maximum is found between 40° and 60° N., and a general depression below the mean line is found between 10° S. and 30° N., a second maximum is found between 20° S. and 40° S.

and a minimum about 50° S. In the temperature curves for the two epochs the variations from the mean are so small that no definite relations are evident.

In plotting the rainfall curves the values were first smoothed by the formula $\frac{a + 2b + c}{4}$. Thus smoothed the curves for 1905–1906 show a maximum in the northern hemisphere, a marked minimum in 10° to 30° S. and a second maximum about the 50th degree of latitude south. The results show that when the solar radiation is above normal in July, the northern hemisphere land surfaces are wet; while, when the radiation is low, they are dry. On the other hand, when the radiation is above normal the land surfaces are dry in the tropical zone in the southern hemisphere and wet in high latitudes, while the reverse is the case when the radiation is below normal, as is shown by a similar plot made for the years 1910–1911.

Turning to the results for 1917, shown by the fine line, it is seen that the departures above and below normal are much greater than in the preceding years, corresponding with the greater excess of solar radiation. In the case of the pressure the northern maximum is not only more intense, but is found further north, the equatorial depression is greater, as is also the depression about the 50th latitude south and there is a large excess about the 60th latitude south. It is regrettable that data are not available from more southern latitudes.

The curve of temperature for 1917 shows two maxima, one about 40° to 50° N. and the other about 40° to 50° S., corresponding to the regions of low pressure found over the land surfaces of America, of Asia and of Australia.

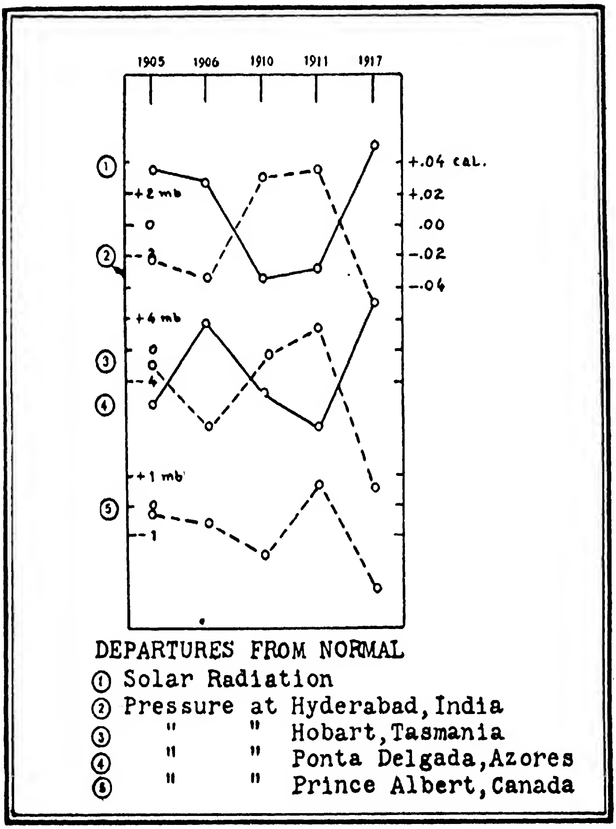
The smoothed curve of rainfall shows maxima between 30° and 40° N. and in the southern tropics. There are deficiencies in the north tropical and south temperate zones.

When the pressure at individual stations is plotted for the successive Julys it is found that at stations near the great centers of action in the atmosphere the pressure follows more or less the changes of solar radiation.

This fact is illustrated by Fig. 209, in which curve 1 shows a plot of the solar radiation for the successive Julys considered (see Table XXV); curve 2 shows a plot of the pressure for the same months at Hyderabad within the low pressure of southern India; curve 3 shows the pressure at Hobart in the Tasmanian low center; curve 4 shows the pressure at Ponta Delgada in the Atlantic high pressure, and curve 5 the pressure at Prince Albert

in the low-pressure belt of central North America. In the regions of prevailingly low pressure, the pressure tends to go opposite to the solar radiation, while over the Atlantic, and probably also over the Pacific, the pressure changes directly with the

FIG. 209



solar radiation. However, owing to the fact that the pressure at any given place is subject to two variables, namely, the change in solar radiation and the shifting of the centers of action, the pressure at any given place rarely follows the solar radiation

even when the annual period is eliminated by taking the pressure for the same month in different years.

This is clearly seen from the values of the departures in central North America given in Table XXVI.

TABLE XXVI

DEPARTURES FROM NORMAL OF SOLAR RADIATION AND OF PRESSURE IN CENTRAL NORTH AMERICA

Year	1905	1906	1910	1911	1917
Solar radiation	+ .034	+ .024	— .025	— .021	+ .051
Prince Albert—	—0.3	—0.7	—1.7	+0.6	—3.7
Omaha	—0.7	+1.7	—1.3	+0.0	—1.7
Nashville	—0.9	—0.5	—1.3	+1.7	—0.4
Galveston	—0.2	—1.0	+0.3	+2.0	+1.3
Mobile	—0.3	—1.4	+0.1	+1.7	+0.7

Note: The solar radiation is measured in gram calories per sq. cm. per minute and the pressure in millibars and tenths of a millibar.

At most of these stations for four out of five years the sign of the departure of pressure is the reverse of that of solar radiation; but, owing to the movement of the area of deficiency, the year of agreement is different for different parts of the country. These results indicate clearly that progress cannot be made in the study of solar relations by means of the observations at any one place. In order to understand and predict solar influence on the weather, it is necessary to study changes over wide areas, and if possible to study the whole atmosphere as a unit.

For studying the relation between solar radiation and the weather at the time of the equinoxes, there is but little solar data for March; but for October the very low mean values of the solar radiation for that month in 1913 allows a study of the effect of diminished solar radiation. By comparing the weather of 1913 with that of 1914, when the solar radiation was slightly above normal, a study can be made of the effect of an increase in solar radiation at that epoch of the year.

The results are shown in Figs. 215 and 216. From Table XXIV it is found that the mean value of solar radiation in October, 1913, was .068 calories per square centimeter per minute below the normal value, or about 3.5 per cent below. The world weather conditions for that month are found in the Reseau Mundial.

The charts show that over the whole of the equatorial zone, except a part of the Pacific Ocean, the pressure was much above the normal, being more than two millibars above in equatorial

Brazil, in equatorial Africa and in parts of the region to the north of Australia. Over the oceanic basins near the 40th degree of latitude, where the pressure is normally high in October, it was generally below normal; while in the neighborhood of Alaska and Greenland, where the pressure is normally low in October, it was above normal in October, 1913. The pressure was also below normal in northern Siberia and in the region of the Great Lakes in North America. The deficiencies of pressure are somewhat north of the regions of the usual centers of high pressure, but, on the whole, the effect of the decreased solar radiation was to flatten out the normal differences of pressure on the earth and to diminish the normal atmospheric circulation. The temperature was above normal in eastern Asia, in the neighborhood of Iceland and in the eastern United States, the regions in which it might be supposed that a decreased atmospheric circulation would result in a higher temperature. It was also generally above normal in the tropics, probably because of both a decreased atmospheric circulation and a decreased rainfall. It was colder than usual in northern Russia, in Canada and in the central United States, in all of which the distribution of pressure indicates a greater prevalence than usual of polar winds.

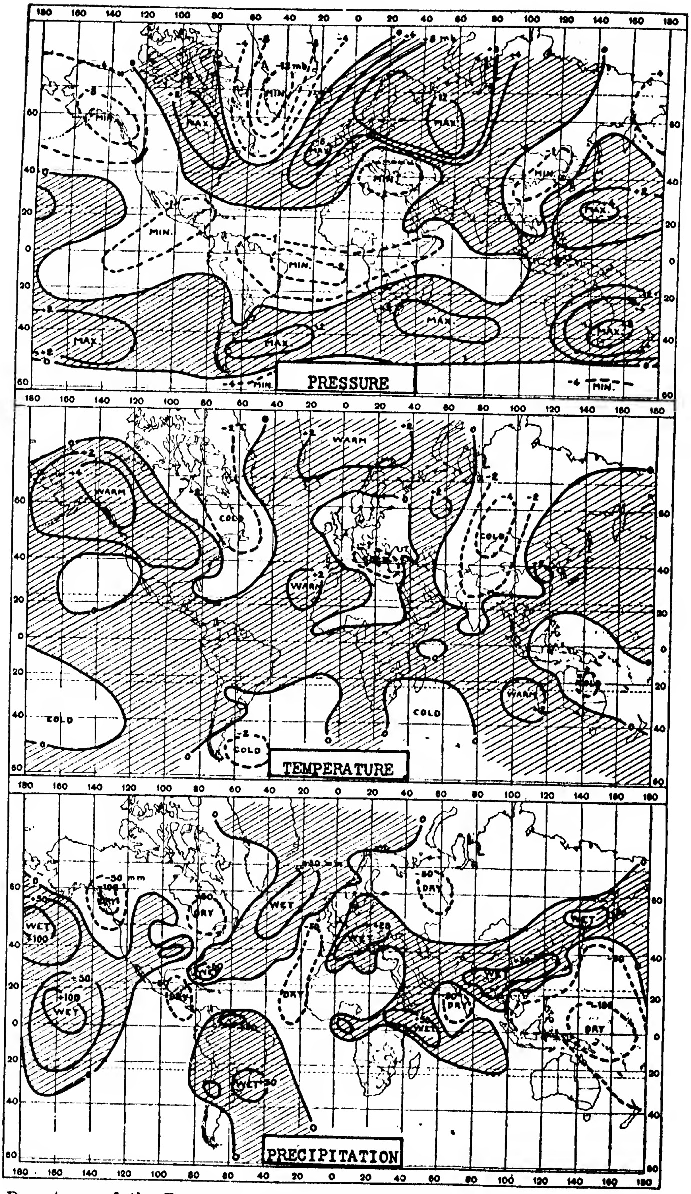
There was a deficiency of rainfall throughout the larger part of the tropical belt especially to the south of the equator. There were also large areas of deficiency in eastern Asia and in the north Atlantic near Iceland, while there were excesses in southern Russia, the western Atlantic and in Canada.

Between October, 1913, and October, 1914, the solar radiation increased about 4 per cent. The effect of this increased radiation on the world's weather is found by subtracting the mean pressure, temperature and precipitation in 1913 from the means at the same places in 1914.

The collection of data in the Reseau Mondial was again used for this purpose and the resulting departures of 1914 from 1913 are shown in Fig. 210.

It is seen that with the increased radiation there was a fall of pressure throughout the equatorial zone, except from about the 110th to 180th degree of east longitude (about one fifth of the whole). There was a striking rise near the 40th degree of south latitude, so that a belt of increased pressure stretches entirely around the world. In the northern hemisphere there was an increase of pressure in the Atlantic and Pacific oceans between 30° and 40° N. and a much greater increase over northern Europe and northwestern Asia and also an increase in the region of the

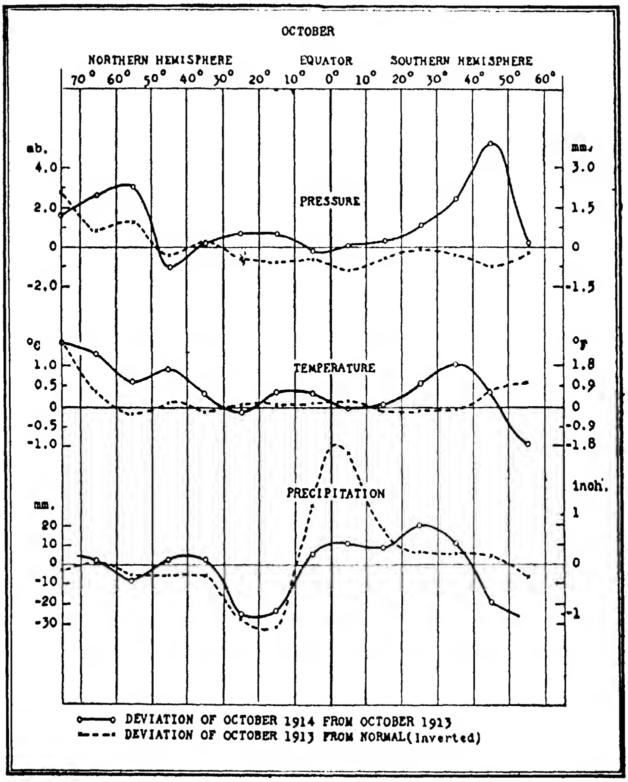
Fig. 210



Departures of the Pressure, Temperature and Rainfall of October, 1914, from October, 1913

Great Lakes in Canada and the United States. At the same time there was a marked intensification of the barometric depressions over the Aleutian Islands and South Greenland and also an intensification of the belt of low pressure in high southern latitudes

FIG. 211



Zonal Effect of Changes in Solar Radiation in October, 1913 and 1914

as is shown by the decreased pressure at the Orcadas and at Macquarie Island.

The departures of pressure, temperature and precipitation of October, 1914, from those of 1913 were averaged in zones of 10° of latitude and the results are shown by the continuous lines in Fig. 211. Two maximum of pressure are clearly shown by the

upper curve, one at 50° to 60° N. and a second at 40° to 50° S., while there is a depression at the equator. The temperature shows a maximum in high northern latitudes and between 30° to 40° S., while it is nearly normal at the equator. The rainfall shows a maximum in the equatorial and southern tropical belt and a minimum at 20° N. and 50° S.

The departures from normal for October, 1913, were also averaged in 10° zones of latitudes. These departures are shown by the broken curves plotted inversely. That is, the minus quantities are above the line and the plus below. A marked excess of pressure and deficiency of rainfall is found in the equatorial zone between 10° N. and 10° S. with nearly a normal temperature.

Both the pressure and temperature diminished toward the polar regions. In other words, with decreased solar activity at that season the air is not drawn off from the polar regions to the equatorial belt. Stagnant conditions resulting from a decreased atmospheric circulation allow the surface air to be chilled by radiation in high latitudes so that the temperature falls below the normal. The rainfall is greatest at 10° to 20° N. latitude and least at the equator. In plotting the data for October, 1913, in Fig. 211, the rainfall curves were smoothed by the formula $\frac{a + 2b + c}{4}$.

YEARLY MEANS OF SOLAR RADIATION AND WEATHER

The simultaneous variations of the yearly means of solar radiation and of weather is evident from the comparison in Fig. 212 in which the yearly rainfall of the central United States, between the 80th and 110th meridian, the rainfall of southern Brazil, as reflected in the depth of the River Parana, and the percentage of rainfall for all of Australia are compared for a number of years. The rainfall in the United States and southern Brazil oscillated directly with the solar radiation during the interval covered, while the rainfall of Australia was inverted.

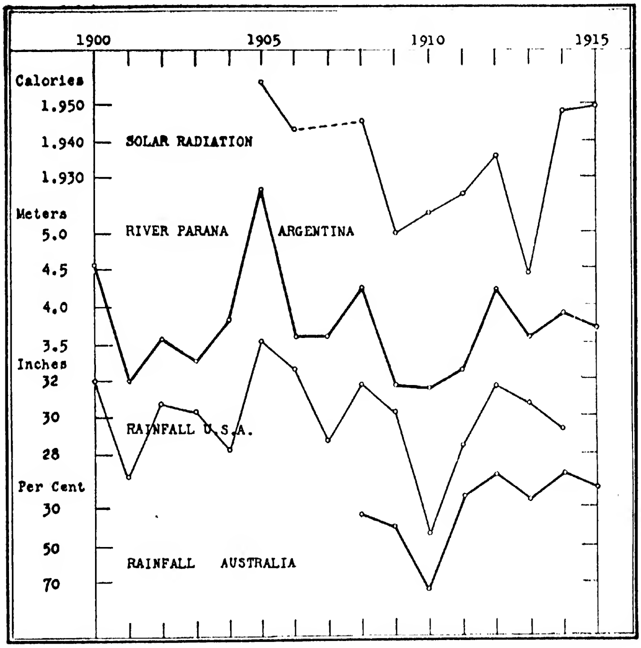
These measurements of the Smithsonian Astro-physical Observatory clearly indicate the existence of a three-to-four-year change in solar radiation, Sir Norman Lockyer noticed the tendency to a three-to-four-year change in pressure, rainfall, etc., which he believed to be due to changes of solar radiation connected with solar prominences. Evidence gathered from observations made at the Observatory of the University of La

Plata, Argentina, indicate that the changes are probably also associated with a variability in the intensity and amount of faculæ.

ELEVEN-YEAR PERIOD IN SOLAR RADIATION AND WEATHER

Dr. C. G. Abbot has shown that the intensity of solar radiation varies in a general way with the sunspots. When the area

Fig. 212

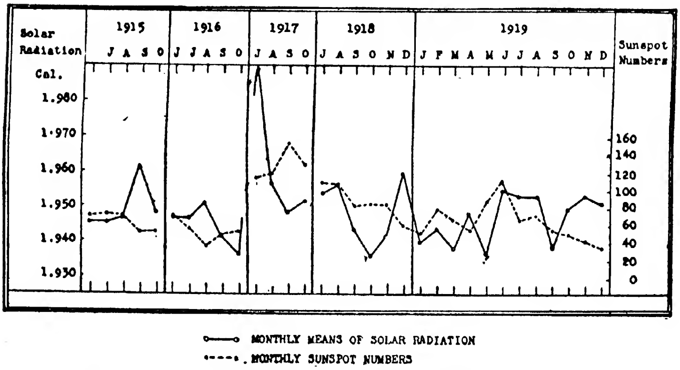


Comparison of Yearly Rainfalls with Yearly Means of Solar Radiation

and frequency of these increase the solar radiation also increases, but a detailed comparison shows that there is no close relation between the two. In Fig. 213 the monthly means of solar radiation are plotted together with Wolfer's sunspot numbers for the years 1915 to 1919. This plot shows that the maxima and minima of the shorter oscillations of sunspots have little apparent relation with that of solar radiation.

When the yearly means are compared, however, as in Fig. 214, the relation between the solar radiation and the sunspot numbers

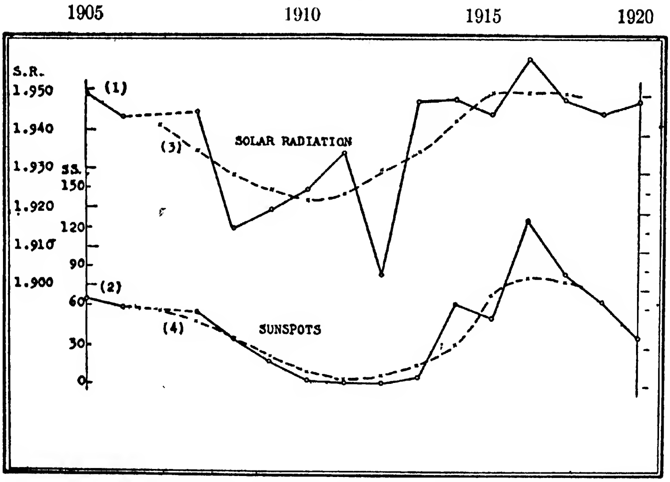
FIG. 213



Monthly Means of Solar Radiation Compared with Monthly Sunspot Numbers

is more evident, except that the solar radiation has a variation of three to four years which is not evident in the sunspot num-

FIG. 214



Comparison of Yearly Means of Solar Radiation and Yearly Means of Sunspot Numbers, Using Same Months for Each in Forming Means

bers. In Fig. 214 the annual means of solar radiation are plotted above the mean of Wolfer's sunspot numbers for the

same months of the year as those in which the solar observations were made.

The resemblance between the two is closer when the solar radiation values are smoothed. There appear to be oscillations of three to four years in solar radiation which do not show appreciably or not at all in sunspots. Trial was made of smoothed means of three, four and five years of solar radiation and the means of four appeared best to smooth out the shorter oscillations. The means of three and five can be placed under the central year, thus the mean of *a*, *b*, *c*, can be placed under *b* and the mean of *a*, *b*, *c*, *d*, *e*, can be placed under *c*; but the mean of *a*, *b*, *c*, *d*, falls between *b* and *c* and the mean of *b*, *c*, *d*, *e*, falls between *c* and *d*. For this reason the means of each four consecutive years were further smoothed by taking the means of each two consecutive means. This is equivalent to the formula

$$\frac{a + 2(b + c + d) + e}{8} \quad \text{or} \quad \frac{b + c + d + \frac{1}{2}(a + e)}{4}$$

The solar radiation values smoothed in this way are shown by the broken curves in Fig. 214. The correlation between these smoothed values of solar radiation and similarly smoothed sunspot number is 0.89 ± 0.07 which considering the broken character of the observations of solar radiation and the admitted fact that the measures are not yet perfect seems a satisfactory agreement. The correlation ratio *b* (see Appendix B) comes out 0.0004. That is to say for every increase of 100 in the relative sunspot numbers the solar radiation increases 0.040 calories or somewhat over 2 per cent.

A great many studies have been made in regard to the relation between the variations of the weather and sunspots, but all investigators agree that weather conditions are far more variable than the sunspot numbers. It will be seen by comparing the curves in Figs. 112 and 114 that in order to study the relation between weather conditions and sunspot numbers it is necessary to smooth out the three-to-four-year oscillation in the weather.

In order to study the influence on the weather of the variation in solar radiation corresponding to the sunspot period the monthly and annual means of pressure and rainfall were collected from all available sources for every part of the world. Averages were obtained for the years about sunspot maximum and minimum for each month of the year and for the annual means by means of the scheme outlined in Table XXVII.

TABLE XXVII

SCHEME FOR OBTAINING MEANS OF PRESSURE, TEMPERATURE AND RAINFALL AT THE TIMES OF SUNSPOT MAXIMA AND MINIMA

Years of Sunspot maxima	*Years before*		*Sun-spot max.*	*Years after*			*Years before*			*Sun-spot min.*	*Years after*		*Years of Sunspot minima*
	2	*1*	*0*	*1*	*2*	*3*	*3*	*2*	*1*	*0*	*1*	*2*	
1860	...	...	...	...	...	...	...	...	...	...	...	...	1867
1870	...	...	...	...	...	...	...	...	...	...	...	...	1878
1883	...	...	...	...	...	...	...	...	...	...	...	...	1889
1893	...	...	...	...	...	...	...	...	...	...	...	...	1901
1906	...	...	...	...	...	...	...	...	...	...	...	...	1913
1917	...	...	...	...	...	...	...	...	...	...	...	...	....
Means	...	...	...	...	...	...	...	...	...	...	...	...	Means

The mean values about maximum and minimum were then smoothed by the formula given above for means of four and the values under the years of minimum sunspots were subtracted from the values under the years of maximum sunspots in order to obtain the difference between the years of maximum and minimum sunspots. The values of the differences of atmosphere pressure for the year and for the seasons December to February and June to August were then plotted on charts as shown in Fig. 215.

The charts show that the pressure is lower at the time of maximum sunspots in the equatorial zone (20° N. to 20° S.) at all times of the year. The differences of pressure are, however, much less than in the case of the monthly means previously given and, hence, lines are drawn for smaller intervals. The fall of pressure is especially noticeable in the humid regions of the earth like the regions between northern Australia and Africa and between the Gold Coast of Africa and the northeast corner of Brazil.

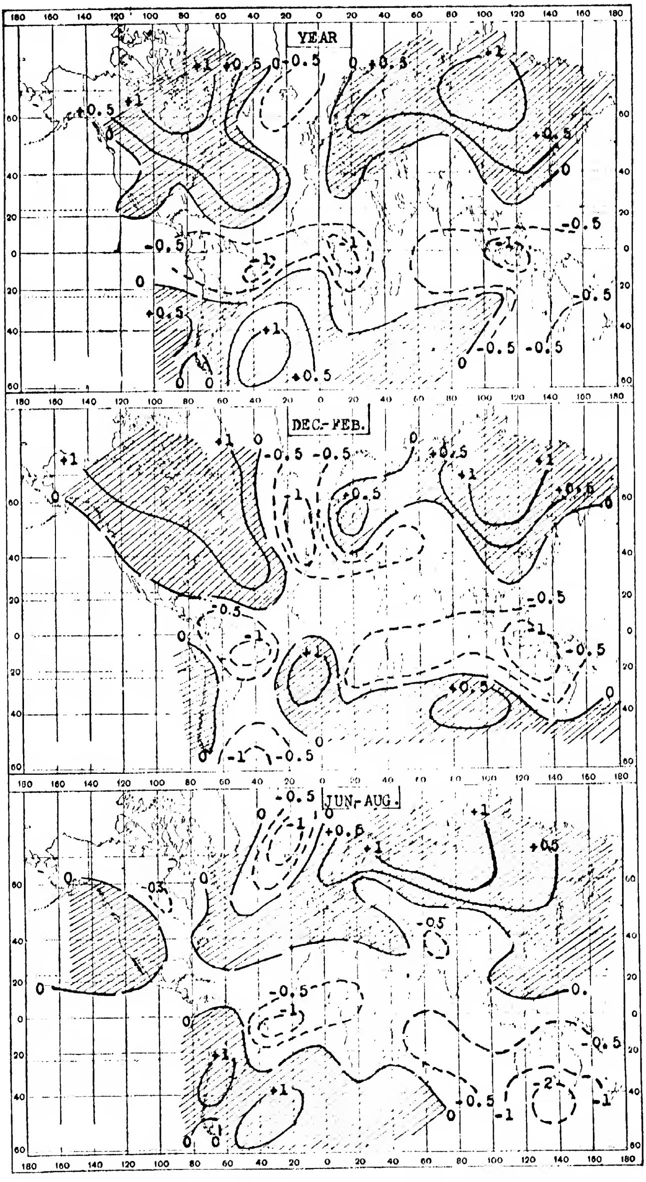
In the winter time of each hemisphere there is an excess of pressure over the continents, except in Australia, and a defect over the oceans in high latitudes. In the summer time of each hemisphere there is a defect of pressure over the continents between the equator and about 50° N. and an excess over the oceans in temperate regions.

The researches of Köppen, Nordman, Walker and others show that the temperature at sunspot maximum is lower in both equatorial and temperate latitudes than at sunspot minimum, but the researches of Walker [5] indicate that it is higher at sunspot maximum in very high latitudes of the northern hemisphere.

The annual difference in rainfall between sunspot maximum and sunspot minimum is shown in Fig. 216. These differences

[5] Memoirs of the Indian Meteorological Department, Vol. 21, pt. 11, p. 61.

FIG. 215



Mean Differences of Pressure between Maximum and Minimum Sunspots

were derived from smoothed means in the same way as were those of Fig. 215. The chart brings out clearly the excess of rainfall in the equatorial belt.

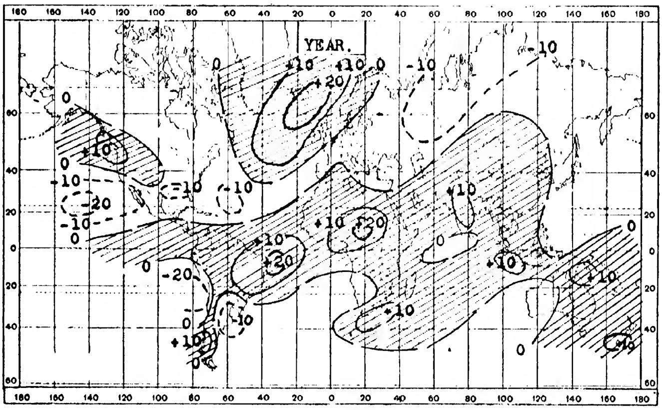
Fig. 217 shows a plot of the zonal distribution of pressure, temperature and rainfall in the sunspot period.

SUMMARY OF RESULTS

The results of the preceding discussion may be summed up as follows:

1. Every increase of solar radiation lowers the pressure within the tropics and increases the pressure in latitudes 40° to 60°,

Fig. 216



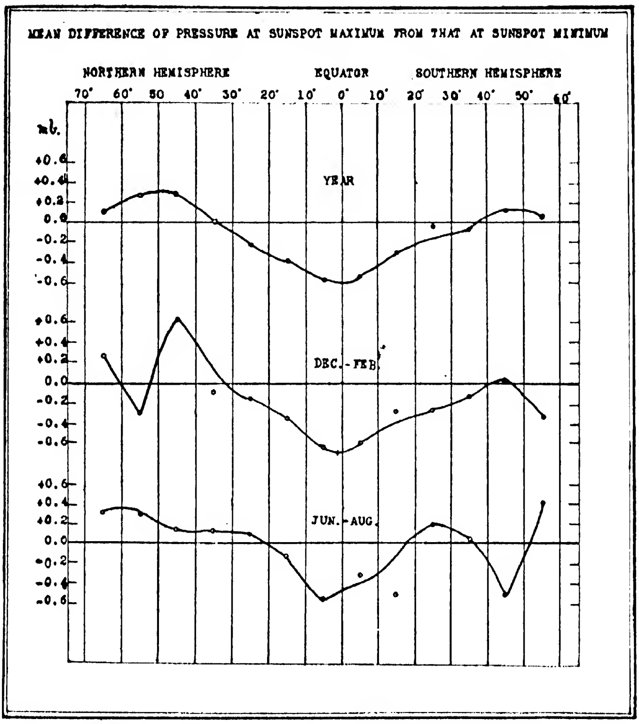
Distribution of Differences of Precipitation between Sunspot Maximum and Sunspot Minimum. Shaded areas show greater rainfall at sunspot maximum.

whether the increase of solar radiation be for a few days, for months, for years or for long periods as in the sunspot period.

2. Near the Arctic Circle over the oceans the pressure also decreases when solar radiation increases. Probably there is an increase again about the pole, but the only evidence of this is the data collected by Dr. G. C. Simpson for the study of barometric surges about the south pole.

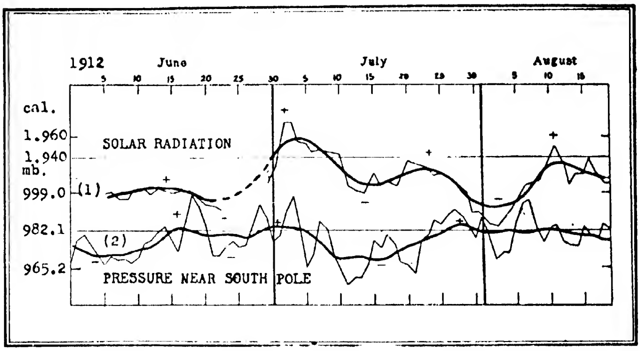
Fig. 218 shows a copy of his plot of the ten-day means of atmospheric pressure at McMurdo Sound and above this curve is plotted a broken curve showing ten-day means of solar radiation

Fig. 217



Variation of Sunspot Influence on Pressure with Latitude

Fig. 218



(1) Ten Day Means of the Value of Solar Radiation Observed at Mt. Wilson, Cal.

(2) Ten Day Means of Atmosphere Pressure Observed at Framheim on the Edge of the Antarctic Continent (78° S)—After Simpson

for the same interval. The solar observations are incomplete, there being many days missing; but the resemblance between the curves seems evident, and shows that the pressure on the Antarctic continent oscillates in the same way as do the solar changes, unless there is a lag of ten days or more in the effect which seems improbable.

3. The fall of pressure with increased radiation occurs near the equator at every season, but the air which passes outward to higher latitude as a result of this fall increases the pressure over the continents in winter and over the oceans in summer, in other words at each season it goes to the regions which are coldest for the latitude.

4. With increased solar radiation the pressure falls over the central areas of the continental masses in summer.

5. The permanent low pressures near Iceland and the Aleutian Islands and doubtless those near the Antarctic continent are intensified with increased solar radiation at all times of the year, probably because of the greater contrasts in temperature resulting from the increased pressure over continents and oceans in high latitudes.

6. The excess of pressure resulting from air removed from the area of deficient pressure within the tropics is found in latitudes to the north of the normal position of the centers of high pressure in temperate regions.

7. The more intense the solar radiation the greater the fall of pressure within the tropics, the wider the belt of diminished pressure and the higher the latitude in which are found the zones of excess of pressure. With very high solar values as in July, 1917, the maximum excess of pressure is found to the north of the 60th parallel in the northern hemisphere.

8. The areas of low pressure over the continents in summer intensify and the central areas move northward. In North America the central area of diminished pressure was found on the Gulf Coast with a moderate excess of radiation in July, 1906. With a greater excess in July, 1917, it moved northward to central Canada, being at an intermediate position in 1905 with an intermediate excess of solar radiation.

9. The belt of greatest fall of pressure in the tropics with increased solar radiation moves north and south with the sun. In July it is found north of the equator, in October it is found along the equator itself, and in January it is found south of the equator.

10. With solar radiation below normal the effects for different

regions for the same time of year are the reverse of those when there is an equivalent excess of solar radiation.

11. There are hence three variables which influence the pressure and other weather conditions at any one place on the earth's surface. These are: first, the variation in intensity following variations of intensity of solar radiation; second, an annual period, as a result of which in some parts of the earth, as over the continents and oceans of temperate latitudes, the conditions following changes of solar radiation are reversed between summer and winter; and third, a movement of the centers of action north and south of their mean position with the varying intensities of solar radiation. As a result of these three variations the weather at very few places on the earth shows a simple direct influence of solar variation. Even when the annual period is eliminated by taking the same month in succeeding years the two remaining variables cause the weather at any given place to follow the solar radiation, sometimes directly and sometimes inversely. These reversals in the case of the pressure are illustrated in Table XXVI. It follows from this fact, that the effects of solar radiation cannot be understood and properly interpreted from the observations at any one station, but must be studied from a network of stations embracing the whole world if necessary.

12. There is a lag in the solar effect near the centers of action proportional to the duration of the solar change. If the duration of an increased solar radiation is no greater than a day, the lag at the centers of action is only a few hours, if the high or low solar radiation continues for several days the lag may amount to two or three days, if the period is near the length of a year the lag is nearly a month, while if the period of change is eleven years the lag may amount to many months or to a year. In general, if one takes the interval from maximum to maximum or minimum to minimum the lag is about one twelfth of the length of the interval, although it may vary on either side of this mean. Thus in the daily period of temperature the lag is from one to three hours according to locality.

13. From the centers of action a series of waves move outward, in general passing from higher to lower latitudes, or in other words moving from pole toward equator with a velocity inversely proportional to the interval of time between the maxima at any given place. Thus if the interval between succeeding maxima is one or two days the waves move very rapidly, while if the interval is five to ten days they move more slowly and if the interval is a month or more they move still more slowly.

The evidence indicates that these atmospheric waves are due to changes in solar radiation of different intensities and of different intervals of duration. The shorter changes in solar radiation produce rapid moving waves. The pressure falls rapidly in the equatorial zone and rises rapidly in higher latitudes, and as the solar outbreak quickly disappears a return wave of higher pressure moves rapidly to the equatorial region. On the other hand, when the increase of solar radiation is of longer duration and decreases more slowly the returning wave of pressure moves more slowly. In other words, the rate of progress of the pressure waves is determined by the rate of change in solar radiation and, since there may be on the sun several different classes of solar changes at the same time, there are in the atmosphere similar classes of atmospheric waves moving with different speeds.

Up to the present the study of the effects of solar changes on the atmospheres are not sufficient to indicate the exact manner in which the atmospheric waves are formed. It is evident that with increased radiation the pressure falls at the equator and increases in higher latitudes and the more intense the radiation the higher the latitude and the greater the excess of pressure.

It is not clear, however, whether the pressure centers are displaced in latitude and longitude, by the solar change, so that they swing about the central areas of the oceanic and continental areas, and the waves are secondary phenomena; or whether the waves are primary phenomena formed by air forced by compression from the equatorial zone and returning in the form of waves. In the case of atmospheric waves of a few days' duration the observations indicate a continuous succession of waves moving equatorward.

To test the question as to whether the slow atmospheric changes gave evidence of waves moving northward as well as southward the data published by Sir Napier Shaw in his pamphlet entitled "Meteorology of the Globe in 1911," p. 147, were averaged each month for each of the sixteen zones into which the earth was divided, then three sets of correlations were obtained for each hemisphere separately. (1) The correlation between the monthly mean temperature in each zone and the mean temperature in the same zone one month later. (2) The correlation between the monthly mean temperature in each zone and that in the zone 10° farther south one month later and (3) The monthly mean temperature in each zone and that in the zone 10° farther north one month later.

The results were as follows:

TABLE XXVIII

CORRELATION BETWEEN MONTHLY MEAN TEMPERATURES A MONTH LATER

	Same Zone	10° *South*	10° *North*	*No. of Cases*	*Probable Error of Maximum Correlation*
Northern Hemisphere....	+ .15	+ .32	+ .17	88	± .09
Southern Hemisphere.....	+ .34	+ .02	+ .35	66	± .11

This table indicates that the maximum correlation is 10° farther south in the northern hemisphere and 10° farther north in the southern hemisphere. In each case the drift is toward the equator. The number of cases is 154 and the correlation is 0.33 with a probable error of ± 0.07. That is the correlation is about five times the probable error. For drift away from the equator the correlation is plus, but is very small and not much greater than the probable error. The evidence is that in all classes of waves, from the very shortest to the very longest, the drift follows the natural tendency of the polar current toward the equator, while solar changes determine the sequence, intensity and speed of the waves.

It may be stated as a general law that *in each cycle of change in solar activity, whether of long or short period, the effect in the temperate zone begins in high latitudes, progresses eastward and equatorward with a velocity inversely proportional to the length of the solar cycle and dies out in low latitudes. The more intense the solar outbreak the higher the latitude in which the effect begins and the greater its intensity.*

CHAPTER XI

PHYSICS OF THE AIR IN RELATION TO SOLAR AND TERRESTRIAL RADIATION

SUMMARY

The changes in the physical state of the atmosphere resulting from variations in the intensity of solar radiation are discussed.

It is shown that the water vapor in the atmosphere is a very powerful absorber of solar radiation in regions where vapor pressure is high and that 50 per cent, or more, of the incoming radiation may be absorbed by the atmosphere. When broken clouds are present it is probably more than 50 per cent.

Illustrations are given of the intensity of solar radiation at different latitudes and at different times of the year. It is shown that there are two maxima of solar radiation at the equator during the year and that the quantity of solar radiation at high latitudes in summer is greater than that at the equator.

A calculation is made of the mean rise of temperature of the atmosphere in the tropics which is implied by the observed fall of pressure attending an increase of solar radiation of about one per cent.

In the case of the monthly mean changes the change in the temperature of the atmosphere necessary to produce the observed change of pressure is found to be only a fraction of a degree centigrade, but the mass of air involved in the change is so great that the amount of air moving off to higher latitudes represents an enormous amount of work when measured in human standards of labor.

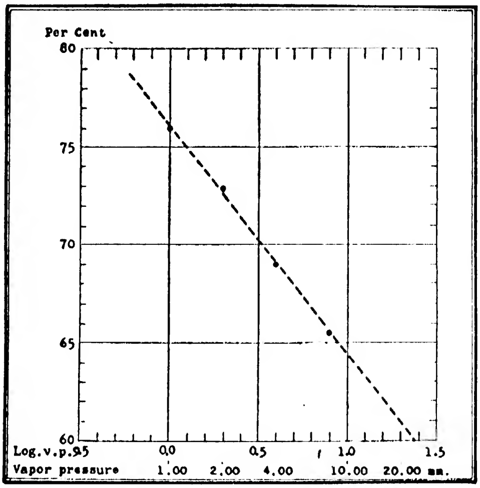
The complexity of the various processes involved in the absorption, reflection, radiation, etc., of solar heat radiation by the atmosphere is shown by quotations from a study of the subject by Dines.

To explain fully the facts presented in Chapter X would require a greater knowledge of solar physics than we now possess, but in general the facts presented by the charts fall in line with accepted views of the physical processes in the atmosphere. Two of the most important of these processes are the absorption of heat by the atmosphere and by the soil and the variation in the duration and intensity of the solar radiation with the time of year.

There are various absorbing gases in the air such as carbon dioxide, ozone and water vapor. Since the first two gases are in very small quantities, the largest absorption of heat is by water vapor. The amount of this absorption is indicated by data furnished me by A. F. Moore from observations at the astro-physi-

cal observatory at Calama made through an air mass equivalent to two atmospheres at that place. Observations made on 57 days with different vapor pressures and different values of the vapor-band ratio were plotted on coördinate paper and a mean curve was drawn from which were read the values plotted in Fig. 219. In this figure the vertical scale shows the percentages of transmission of solar energy, while the horizontal scale is proportional

FIG. 219



Percentage of Transmission of Solar Radiation at Different Vapor Pressures in the Atmosphere

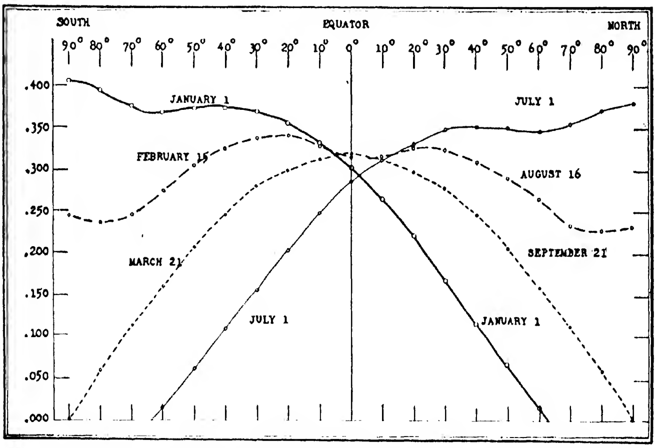
to the logarithm of the vapor pressure. Below is written the amount of vapor pressure in millimeters.

The plot shows that when the vapor pressure is below one millimeter at Calama between 75 and 80 per cent of the solar radiation reaches the earth's surface. As the vapor pressure increases, the scattering and absorption of the solar radiation by the air also increases, until at 20 mm. not much more than 60 per cent reaches the earth's surface. The density of the air mass at Calama is considerably less than that at sea level, and the mean atmospheric mass through which the solar rays pass in a day is more than two atmospheres, so that it is evident that at any place in the tropics where the vapor pressure exceeds 20 mm. 50 per cent or more of the solar radiation will be absorbed by the

transparent water vapor, assuming that the part not transmitted is absorbed by the air. When there are clouds to absorb and reflect the light the absorption is probably much greater. In the case of perfect reflection where 50 per cent was absorbed in the first passage through the air, and 25 per cent in the second, the total would be 75 per cent.

Another important condition is that the sun changes its position in the sky as much as 47° during the course of the year and the length of the day as well as the angle of the sun above the

FIG. 220



Relative Mean Vertical Intensity of Solar Radiation at Different Latitudes

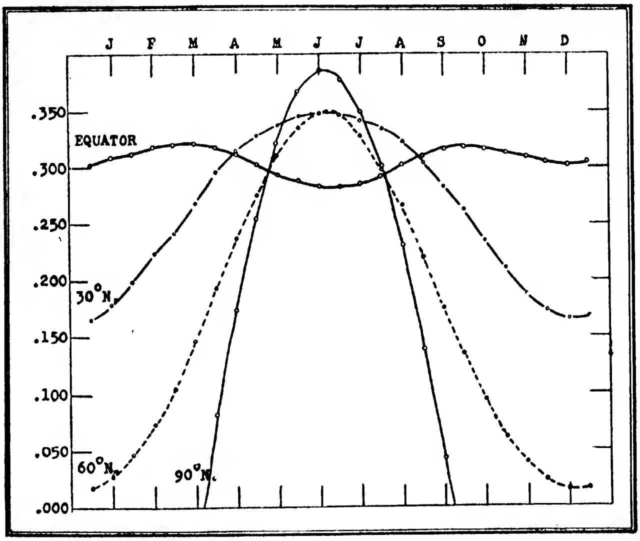
horizon varies greatly in high latitude. Because of the change in the position of the place where the sun is vertical and because of the change in the length of the day, the amount of solar radiation reaching any latitude varies greatly, as will be seen from Figs. 220 and 221. Fig. 220 shows the relative mean vertical intensity of solar radiation at different latitudes at different times of the year and Fig. 221 shows the annual variation in the intensity of solar radiation at the equator and at each increase of 30° of latitude to the north pole. At southern latitudes the effect would be similar, but somewhat more intense, because the sun is nearer the earth.

The plots were constructed from computations made for the Smithsonian Astro-physical Observatory. The relative intensity was found by dividing the mean intensity for 24 hours (J) on a

horizontal surface at the top of the atmosphere by the mean solar constant (A_0) and allowing for the number of hours of sunshine in each latitude.

Fig. 220 shows that on January 1 the maximum intensity of solar radiation is at the south pole, there is a secondary maximum at 40° S. and a minimum around the north pole. By February the maximum of radiation has moved to 25° S. and by March has reached the equator. It then moves northward, reaching

Fig. 221



Annual Period in the Intensity of Solar Radiation at the Equator and at Latitudes 30, 60, and 90 Degrees North

25° N. about the 1st of May and reaching the north pole in July, when there is a primary maximum at the pole and a secondary maximum at 40° N. After that the changes follow the reverse course from the northern hemisphere to the southern. The only time of the year when the radiation is symmetrical about the equator is at the equinoxes, at which time there is an increase in the atmospheric circulation in both hemispheres and a deepening of the polar cyclones as explained in Chapter III.

Fig. 221 shows the annual changes in solar intensity at selected latitudes. At the equator there are two maxima, one at each

equinox. This double period each year is combined with an annual period, due to the fact that the sun is nearer the earth in December than in June. In higher latitudes the annual period is more symmetrical. North of 60° latitude the intensity of solar radiation is greater than at the equator from about May 10 to August 1.

There are two ways in which the atmosphere may be heated: first in humid regions, principally by direct absorption of the solar energy by the vapor of water present in the air and by clouds; second, in arid regions, principally by the absorption of solar energy by the earth's surface, which gives it back to the air by long-wave radiation and by conduction and convection. In the first case, especially if there is much cloudiness, only a part of the increased solar radiation reaches the earth's surface, so that if there is an increased rainfall and an increased atmospheric circulation which tend to cool the air, the temperature of the surface air may not rise above normal and may even fall below normal.

From the charts in Chapter X it is seen that the principal decrease of pressure in the tropics following a temporary increase of solar radiation takes places in humid regions, like the tropical Pacific, the Indian Ocean, the Gold Coast of Africa and the equatorial coast of Brazil, a fact which might be expected because the chief factor in the heating of the atmosphere within the tropics is the absorption of solar heat by the moist atmosphere and not its absorption by the earth's surface as in arid regions like the Sahara and Arizona. In high latitudes in summer where the vapor content of the air is less than in the tropics and the solar radiation is large on account of its prolonged duration (see Figs. 220 and 221) the heating of the earth's surface and the formation of convection currents are probably the chief factors in the heating of the atmosphere. For this reason the low pressures attending increased solar radiation in high latitudes in summer are found over the continents like central Asia and central North America where the conditions of the earth's surface and the dry air are most favorable for this convective warming of the atmosphere.

In the tropics the fall of pressure is a measure of the increase of the temperature of the atmosphere because near the equator the pressure is very little affected by air movement. In that region the atmosphere above any place may be considered as an immense gas thermometer whose change of temperature is measured by the rise or fall of the barometer at the earth's surface.

It is known by experiment that for every increase of temperature of 1° C. (1.8° F.) the air expands 1/273 part of its volume at 0° C. In the free air the expansion probably occurs chiefly in a vertical direction, in which there is least resistance, and the expanded air seeking equilibrium flows off toward regions in which the temperature is low or falling. The remaining air now occupies the same volume as before and, hence, the number of air particles over any given area has diminished 1/273 for each degree of rise of temperature. Consequently there is an equivalent decrease in the weight and the pressure of the air.

At sea level near the equator the pressure over each square centimeter is about 1010 millibars and, hence, for each rise of 1° C. (1.8° F.) in the mean temperature of the atmosphere above any place the pressure will diminish $\frac{1010}{T}$ millibars or 3.37 millibars, taking T as equal 300° on the absolute scale. Consequently for a rise of 0.30° C. (0.54° F.) it will fall 1 millibar.

In January, 1920, the mean pressure within the tropics between the equator and 40° S. was — 0.47 millibars below normal, which from the preceding considerations indicates a mean rise of temperature in the atmosphere within that region of 0.14° C. (0.25° F.) accompanying an increase of 1 per cent in solar radiation. This seems a very small amount when measured as temperature, but when the amount of energy displayed in work is considered it seems very great.

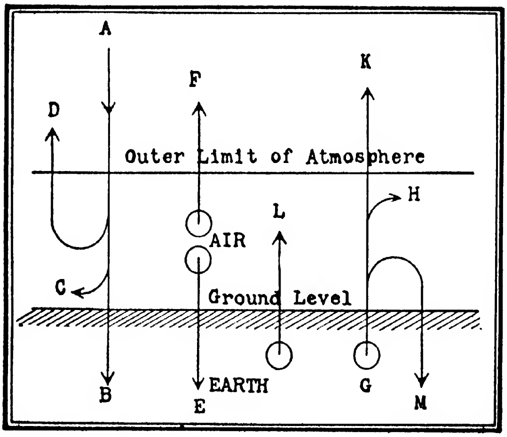
If the mean area of one degree square between latitudes 0° and 40° be multiplied by 40 and 360 so as to get the total area of the zone between 0° and 40° it is found to have the area of 166,820,472 million square meters.

One millibar exerts a pressure equivalent to the weight of 10.2 kilograms pressing on one square meter. Hence, the decrease of pressure of one millibar in that region would be equivalent to the removal of 1,701,568,794 million kilograms or 1,871,725,568,-000 tons. The data show that the principal increase of pressure takes place between 40° and 50° N. and also in far southern latitudes, so that it may be assumed that the greater part of the mass of air removed from the tropics is carried some 60° or 4128 statute miles. With a mean fall of pressure of 0.47 millibars such as found in January this would mean a transportation of 3,631,447,151,000,000 ton miles per month or less, because most of the fall and rise of pressure took place within less than a month.

According to statistics at hand the total haul of all the British

railways in the year 1920 was 10,364,679,882 tons one mile and of the railroads in the United States for six months was 207,281,-000,000 tons one mile. When reduced to the amounts hauled per month, it is seen that the air displaced by an increase of less than 1 per cent of solar radiation was more than 100,000 times greater than could be carried by the railroads of Great Britain and the United States and many times greater than could be carried by all the tonnage of every class of vehicle in the world.

FIG. 222



Illustrating Action of Solar Radiation on the Atmosphere

How complicated the question of atmospheric physics is, will be understood from Fig. 222 taken from a paper read before the Royal Meteorological Society by Mr. W. H. Dines.

In this Fig. 222, the line A indicates the heat entering the atmosphere from the sun, D the amount reflected back, C the amount absorbed, B the amount which reaches the earth, E the amount radiated from the air to the earth, F the amount radiated from the air to space, G the amount radiated from the earth toward space, M the amount of this earth radiation reflected back, H the amount of the earth's radiation absorbed by the atmosphere, K the amount of earth radiation which passes through the atmosphere and goes out to space and L the amount of heat transferred to the atmosphere from the earth by other processes. The two chief processes involved in L are: (1) the absorption of

heat from the earth's surface by evaporation of water vapor and restoring the heat to the atmosphere by condensation at higher levels, and (2) the rising of air heated at the earth's surface transferring the heat to higher levels.

To all of these complex processes of radiation, absorption, transmission, reflection, convection, etc., Mr. Dines [1] has endeavored to assign numerical values basing his estimates on the work of the astro-physical researches of the Smithsonian Institution, of various physicists of Europe and his own researches. Considering the mean for the whole earth and taking one square centimeter per day as the unit, he assigns the following approximate mean values:

A (solar radiation outside the atmosphere) = 720 calories per sq. cm. per day;
B (transmitted to earth) = 300; C (absorbed by atmosphere) = 60;
D (reflected to space) = 360.
G (earth radiation) = 500, M (reflected back) = 60; H (absorbed by air) = 360, K (passing out to space) = 80; E (radiation from atmosphere to earth) = 340; F (radiation from atmosphere to space) = 280.
L (heat passing to atmosphere from earth by convection, etc.) = 200.

Mr. Dines calculates that if the whole of the solar radiation were spread evenly over the earth it would be capable of warming the air about 3° C. (5.4° F.) per day.

But the values given vary greatly for different parts of the earth and for different latitudes and for different conditions of the atmosphere. In a second paper Mr. Dines [2] makes some computations of various factors for certain especial cases.

He divides the air into ten layers, each differing by a pressure of 100 millibars, so that the mass is the same for each. He assumes, as is justified by the laws of radiation, that the radiation emitted by any layer is proportioned to the fourth power of its absolute temperature multiplied by a certain factor, η, called the emissivity; and further that the proportion of the radiation passing through any layer that is absorbed is η and the proportion transmitted is $1-\eta$. It is seen from Fig. 219 that the amount absorbed varies with the amount of vapor in the air. With very

[1] Dines, W. H., *Quarterly Jour. of the Royal Meteor. Soc.*, Vol. 43, p. 151, London, April, 1917.
[2] *Quarterly Jour. of the Royal Meteor. Soc.*, Vol. 46, April, 1920, p. 163.

dry air it is less than 0.20 while with moist air it is more than 0.40.

Mr. Dines made calculations of the atmospheric conditions to be expected over England as a result of atmospheric radiation for many different values of η. The most important of these were when the air was very dry and η small (anticyclonic conditions), the second when the air was moist and η high and also when η was small at the top of the atmosphere and increased to high values near the earth's surface (cyclonic conditions).

The results of the calculation are given in Table XXIX, together with results for similar degrees of emissivity in the equatorial zone.

TABLE XXIX

ATMOSPHERIC CONDITIONS WITH DIFFERENT DEGREES OF EMISSIVITY

				ENGLAND						
Pressure	50mb.	150	250	350	450	550	650	750	850	950
Emissivity	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
Gain or Loss	—14	5	11	9	—6	—26	—30	—35	—40	—44
Emissivity	.50	.50	.50	.50	.50	.50	.50	.50	.50	.50
Gain or Loss	—92	—22	19	24	1	—10	—23	—25	—26	—31
Emissivity	.20	.20	.25	.30	.35	.40	.50	.60	.60	.40
Gain or Loss										
				EQUATOR						
Emissivity	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
Gain or Loss	38	45	24	2	—10	—30	—38	—50	—55	—60
Emissivity	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
Gain or Loss	29	51	22	—4	—12	—31	—40	—45	—50	—57
Emissivity	.20	.20	.25	.33	.42	.50	.60	.60	.60	.40
Gain or Loss	20	21	—7	—19	—41	—52	—50	—41	—24	—26

	ENGLAND				
Condition	E	K + X	K	F + K	C + L
Emissivity	.20	.20	.20	.20	.20
Gain or Loss	480	220	76	391	168
Emissivity	.50	.50	.50	.50	.50
Gain or Loss	630	73	1	273	186
Emissivity	.20-.60	.20-.60	.20-.60	.20-.60	.20-.60
Gain or Loss	628	76	4	342	267
	EQUATOR				
Emissivity	.20	.20	.20	.20	.20
Gain or Loss	588	302	96	433	132
Emissivity	.30	.30	.30	.30	.30
Gain or Loss	699	191	21	328	136
Emissivity	.20-.60	.20-.60	.20-.60	.20-.60	.20-.60
Gain or Loss	794	96	3	360	218

The gain or loss refers to the net gain or loss of the atmospheric stratum in gram calories per square centimeter per day. It is the difference in the values of the net radiation entering at the lower boundary and leaving at the upper boundary of any stratum. It is considered negative where the stratum is losing heat, positive where it is gaining. Or, to put it in another way, a negative sign means that a stratum is being warmed by some means other than long-wave radiation and a positive sign that it is being cooled.

According to Mr. Dines, "the general result of the calculation is to show that the strata from 1000 to 400 millibars pressure are receiving heat from other sources, which may well be solar radiation and the latent heat of condensation of aqueous vapor. The two top strata are receiving heat apparently from solar radiation. The two layers between 400 and 200 millibars are being cooled probably by the mixing by wind of the layers of the troposphere."

He says further:

"But whatever distribution of η be taken the same general loss of heat by radiative processes in the first six layers, 0-7 kilometers, is shown. These layers are radiating more than they receive, the net loss running to about 200 g.c. per day. As already stated most of this is probably supplied by the latent heat of condensation of water vapor and by contact with the ground warmed by the sun. In a previous paper this was denoted by *L,* and 200 g.c. per day as a mean for the earth were assigned to these combined sources of heat. There is also the effect of direct solar heat, *C*, absorbed by the air, and another source of warming that is best discussed with the next two layers. The next two layers covering the height of 7.0 to 11.7 kilometers show on the whole a positive value of about 20 g.c. That is to say, they are together receiving 20 g.c. more by long wave radiation than they are losing. They must also be absorbing some solar radiation which may perhaps be put at 10 g.c., but they are probably above the level at which any appreciable amount of vapor is condensed. Thus a cooling equivalent to 30 g.c. per day or 0.6° C. has to be accounted for. This is no doubt due to the forced mixing of the atmosphere by wind which sends heat downward; such mixing if carried far enough would produce an adiabatic gradient of 10° per kilometer height, whereas the usual gradient is only 6°; it would therefore cool the upper and warm the lower strata."

It is thus seen that Mr. Dines gives a different explanation of the cooling at the top of the *troposphere* from

that given by Professor Humphreys quoted in an earlier chapter.

Mr. Dines says further:

"Of course the whole loss of heat by radiation must be made good by other means since the temperature is not falling. This is the $C + L$ in Table XXIX. [See also Fig. 228.] In the previous paper reasons were given for putting this value at 260 g.c. If the present calculation is right, the 260 g.c. is too high, but the 260 was taken as a mean for the earth, and the present calculation uses the temperatures found over England.

"With regard to the other quantities, a different value of σ is used here giving 705 for the earth's radiation at 283°. In the previous paper it was taken as 500 g.c. at 288° absolute, a value based on Bottomley and King's experiment, but no doubt too low. This makes any comparison difficult. But the value of $K + x$, the net upward radiation at the surface, was estimated without any reference to Stefan's constant as ranging from a small amount for a cloudy sky to an average of 200 for a clear sky. By Mr. Richardson's method, omitting the improbable case of $\eta = .10$ the range is from 55 to 220, a good agreement. $F + K$ is the total loss of the earth's heat and is equal to such part of the sun's heat as is not reflected. Abbot and Fowle give the mean value for the earth as about 430. Here again there is good agreement.

"It is noteworthy that whichever distribution of η be taken the value of F, the calculated upward radiation of the atmosphere itself remains almost unaltered at about 320 g.c. per day as within 10 per cent of the average outward radiation of the atmosphere over England. It is equivalent to the full radiation of a black body at 232° absolute. If we include K so as to have the whole radiant energy given out by the earth, including the atmosphere, the equivalent temperature is 247 absolute.

"The results given above refer to the special arrangement of temperature that prevails over England or Europe at about the same latitude.

"With different temperatures the results would be different, and the cases of a cyclone and anticyclone in England, together with three cases for the equatorial distribution of temperature, have been worked out. Between the cyclone and anticyclone it appears that more heat is being lost by radiation in the cyclone than in the anticyclone, but we can not say that more is being supplied, because the conditions are only temporary and not like the mean values permanent.

"The tropical values differ from those for this latitude inasmuch as the highest layers are accumulating heat by long-wave radiation. This is due to the fact that owing to their low temperature they are giving out very little, and it confirms the belief I have

long held that the low temperature is due to dynamic and not to radiative causes."

Some years ago Abbot and Fowle [3] called attention to the fact that dust in the air, like the appearance of volcanic dust, caused a decrease in the solar radiation reaching the earth's surface, the value *B* in Dines' scheme, and suggested that it might play an important part in meteorological phenomena. Professor Humphreys has accepted this view and constructed an elaborate theory of climatic changes based on volcanic dust. The decrease in the radiation reaching the earth might be caused by reflection and scattering of the solar rays alone or by these combined with selective action on the rays. Professor Humphreys' view is that it is due to selective action on the waves. The shorter waves coming from the sun to the earth are reflected back and scattered, while the longer waves radiating from the earth are allowed to pass freely and the net result is a lowering of the earth's temperature.

Meteorological observations indicate that "water-dust," that is, suspended particles of water or ice crystals in the air do not have the effect suggested by Professor Humphreys. The thinnest layer of cirrus apparently intercepts the radiation of the earth at night, and thus allows the temperature of the surface to rise as the heat received by conduction then exceeds that lost by radiation. Owing to differences in size or chemical character it may be that volcanic dust acts differently; it is worthy of full investigation.

Because the physical processes of the air are so complex and it is impossible to apply laboratory methods to the free air and because such investigations require delicate and expensive apparatus and highly trained observers, our knowledge of these processes has progressed very slowly.

The observations of Pouillet, Violle, Crova, Abney, the Ångströms, Very, Kimball and others and the discussions of Rayleigh, Maurer, Gold, Exner, Humphreys, Dines, Richardson, etc., have contributed much to a knowledge of the subject, but much remains to be done.

Other men may have seen as clearly as did Dr. S. P. Langley that the solution of the problems of meteorology depends on a knowledge of solar radiation and of terrestrial physics, but his penetrating genius which led him to invent the bolometer enabled him to extend the spectrum many times its previously known

[3] "Smithsonian Miscellaneous Collections," Vol. 60, No. 29, Washington, 1913.

length and to found the Smithsonian Astro-physical Observatory. Under the able direction of Dr. C. G. Abbot, aided by such assistants as Fowle, Aldrich, Moore and others, the Institution is accumulating a mass of observations and information which promises to aid greatly in developing the science of meteorology.

In the early development of meteorology it was generally believed, and is still believed by many, that the differences of temperature arising from the different compositions of the earth's surface, the contrast between land and water and the contrast between pole and equator are sufficient to explain all the phenomena of the weather.

Helland-Hansen and Nansen,[4] in an extensive research published by the Smithsonian Institution, have shown that the influence of ocean currents on the temperature of the overlying air cannot be the cause of weather, because (1) the temperature changes of the water are less than those of the air, the air temperature sometimes rising above that of the water and sometimes falling below it; (2) the changes in air temperature frequently precede the changes in water temperature; (3) the changes in air temperature take place over wider areas than the changes in water temperature and both are clearly related to the system of winds prevailing at the time of observation.

The heating of land surfaces cannot be the cause of general storms because these are not most frequent at the time of year when insolation is greatest. For this reason and because the observations made with sounding balloons do not show that the central areas of cyclonic storms in temperate latitudes are warm, the theory of central heating as the cause of this class of storms has been abandoned by most, if not by all, meteorologists.

Dove and more recently Bjerknes have educed the conflict between polar and equatorial currents as sufficient causes for weather changes. The contrasts between cold polar currents and currents from the equator are undoubtedly sufficient to produce cyclones and anticyclones, as explained in Chapter VIII, but in Chapter X it is shown that these waves of cold polar air follow temporary changes in solar radiation and probably have their origin in the effects of these changes of solar radiation on the earth's atmosphere.

There is as yet no absolute proof that weather changes would not occur without changes in solar radiation, but my own

[4] Björn Helland-Hansen and Fridtjof Nansen—"Temperature Variations in the North Atlantic," *Smithsonian Miscellaneous Collections*, Vol. 70, No. 4, Washington, 1920.

researches have led me to believe that without these solar changes there would result a balanced system of atmospheric changes such that the same conditions would return year after year at the same time of day and at the same time of year; while the irregular changes known as weather result chiefly, if not entirely, from the irregular changes in solar radiation.

Long period changes of temperature and rainfall occupying several decades or even centuries for their completion have been investigated by Brückner, Douglass, Huntington, Clough and others. Many different hypotheses have been offered in explanation of these changes but the striking analogy between these changes and the changes of shorter period which are associated with changes in solar radiation is evidence that these also in part at least are due to solar changes.

Even the class of changes found by geologists accompanying the ice ages, or glacial epochs, show striking similarity to the changes illustrated in Chapter X accompanying an increase of solar radiation, and suggest that these also resulted from a great increase in solar radiation, intensifying the tropical rainfall, the oceanic cyclones, and the continental anticyclones of high latitudes.

CHAPTER XII

PERIODICITY IN THE WEATHER AND IN SOLAR PHENOMENA

SUMMARY

A tendency to a repetition of solar radiation values of similar kind is found at intervals of about eleven and sixteen days and is traced to the movement of heated gases from one side of the sun to the other. These heated gases show themselves in the form of solar faculæ. Similar variations were found in the temperature at Buenos Aires.

Short period variations of about 3.5, 7 and 13.5 days were also exhibited by the faculæ and by certain observations of solar radiation. Observations of faculæ for nine years permitted a study to be made of the position of successive outbreaks of faculæ on the solar surface and it was found that these were so related to each other that there was a marked tendency to periods of 3.5, 7 and 13.5 days in their appearance as seen from the earth. From these were traced similar tendencies to repetition in the weather.

A detailed study was made of the sunspot period in pressure, rainfall, temperature and other phenomena at stations all over the world. It was found that the weather conditions were more variable than the sunspots, but when the observed values of the elements of weather are smoothed by getting means of four and two, they show oscillations similar to those of the sunspots. In some cases the maxima of the weather elements were near the maxima of sunspots and in other cases the relation was inverted. The pressure was found to be abnormally low throughout the tropics at the time of sunspot maximum and high at sunspot minimum. The same tendency was found in the region of the North Atlantic near Iceland, in the region of the Mediterranean, and in the North Pacific, near Alaska.

It was also the case for the ocean areas near the south coast of Australia, and near the extreme southern points of Africa and South America.

Over continental areas like North America, Asia and Central South America between 30 and 40 degrees north there is a tendency of the pressure to follow the same trend as the number of spots.

An examination of the sunspot period in weather conditions month by month shows that there is an annual period in the influence of the spots. In the equatorial region the influence of increased spots is more marked in lowering the pressure in January than in July, while in high northern latitudes there is an inversion of this effect, the mean result of which is to intensify the annual changes in pressure over the continents.

There is also a semi-annual period in the influence of the spots probably due to an increase in the temperature contrast between equator and pole in March and September, when the sun is hottest, so that the polar cyclones and the atmospheric circulation in general are intensified. This half-year period corresponds to an intensification of the normal

half-year period explained in Chapter III; but to a remarkable degree, so that in high latitudes, like that of Iceland and Northern Russia in the northern hemisphere and at Punta Arenas and the Orcades in the southern hemisphere, the half-yearly period becomes larger than the yearly period; furthermore, there is a distinct opposition between oceanic and continental stations.

The influence of the sunspots on the rainfall also shows annual and semi-annual changes.

The influence on the air temperature near the surface is to lower the temperature at sunspot maximum both in the equatorial and temperate regions. The lowering of the temperature in the tropics is believed to be due to increased rainfall and air circulation and in temperate latitudes to increased radiation accompanying the increase of atmospheric pressure. In arid regions in the tropics the temperature tends to be higher at the time of sunspot maximum. Also at certain stations in temperate regions the temperature at sunspot maximum is higher in summer and lower in winter than at sunspot minimum.

The snowfall tends to be deeper and icebergs more numerous at sunspot maximum. Tropical rivers like the Nile show maximum heights at sunspot maximum, while rivers in temperate regions like the Parana show an inverse effect.

Data bearing on the effect of increased solar radiation on the daily periods in the atmosphere are as yet meager, but they indicate that all these daily changes are strengthened, at least in arid regions and probably, with some exceptions, in the whole world.

It is evident from the charts and diagrams presented in Chapter X that when there is an increased solar radiation, the areas of low pressure and large rainfall are intensified in the equatorial regions where they are normally low. A fall of pressure in the equatorial zone implies that the mean temperature of the atmosphere rises in that region. The surface temperatures, however, do not show clear evidence of solar influence. They are acted on by the opposing forces of increased solar radiation, tending to raise the temperature, and of increased rainfall and air circulation, tending to lower it. With temporary increases of a few days' length in solar radiation, the surface temperature appears to rise; while with changes of long period, like those accompanying sunspot activity, the surface temperature falls.

In high latitudes over continental areas, the pressure falls in summer and rises in winter with increased solar activity. Over the oceans, the reverse conditions prevail; but, in each case, the tendency is to increase the annual range, although the effect is greatly modified by the displacement of the excesses and defects of pressure toward higher latitudes with increased solar radiation. The amount of change for particular stations and regions remains to be determined.

The influence of the solar radiation on the rainfall is the reverse of that on the pressure. The rainfall tends to be small when the pressure is high and large when the pressure is low, so that in high latitudes its annual range is also increased with increased solar radiation.

The temperature changes are closely related to pressure changes. In high latitudes the temperature tends to be low when the distribution of pressure indicates an increase in northerly winds, and high when the pressure distribution indicates southerly winds. The pressure distribution is undoubtedly caused by an increase in the temperature differences between equator and pole and between continent and ocean, considering the temperature of the atmosphere as a whole; but, when considering surface temperatures in any one region or place, it is easier to explain them as caused by the observed distribution of pressure.

The influence of the solar changes on the annual distribution of pressure, temperature and rainfall during the sunspot period will be considered more fully when treating of the sunspot period.

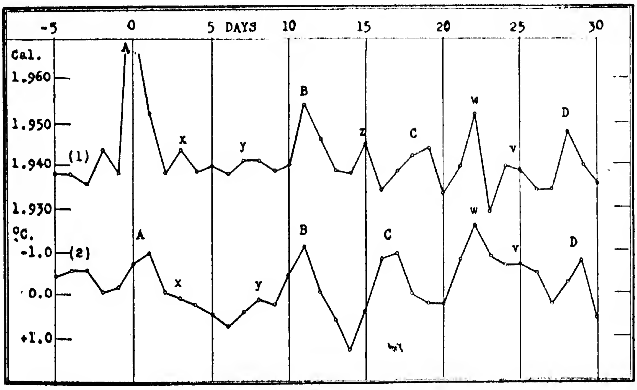
Among the variations in the diurnal and annual periods arising from variations in solar activity there is a series of periodic or semiperiodic changes resulting from the rotation of the sun on its axis. The period of rotation appears to vary with different latitudes and according to the latest measurements, the period of rotation for different latitudes as seen from the earth is as follows: equator, 26.38 days; 30° latitude, 28.34; 60° latitude, 34.11; 80° latitude, 38.95. In the region of the sunspots and faculæ which are usually found between the equator and 20° latitude, the mean rotation is 27.23 days.

In order to determine whether there was any period corresponding to a solar rotation in solar radiation or in meteorological conditions, or if there was any fixed order of sequences, all the observed values of solar radiation above 1.990 between the years 1909 and 1918 were taken from the published reports of the Smithsonian Astro-physical Observatory and averages of all the observations were obtained for each of the five days preceding the maximum and for each of the 30 days following.[1] The same was done for the air temperature at Buenos Aires, and the results are plotted in Fig. 223. As the solar observations were confined to the months between May and November, the winter season of the southern hemisphere, the temperature curve represents winter con-

[1] Clayton, H. Helm—"Variations in Solar Radiation and the Weather," *Smithsonian Miscellaneous Collection,* Vol. 71, No. 3, Publication 2544, Washington, Jan. 15, 1920.

ditions in Buenos Aires and is inverted, that is minus departures are plotted above the line and plus departures below. It is also displaced three days toward the left to allow for a lag in the solar influence. There is no marked indication of the return of the solar maximum at the end of a solar rotation, although there is a secondary maximum at *D* about 28 days later. There is, however, a marked maximum at *B* about 11 days later and this is so persistent a feature in separate curves made for separate intervals, that its relation to some natural cause seems evident. Recent visual observations of faculæ at the Astronomical Observatory

Fig. 223



Mean Values of Solar Radiation and of Temperature at Buenos Aires Preceding and Following Maxima of Solar Radiation

of the University of La Plata, Buenos Aires, appears to prove that increases of solar radiation of a day or two are connected with faculæ on the east and west limbs of the sun as seen from the earth, and vary in intensity with the area and intensity of the faculæ.

Associated with eleven observations of faculæ on the east edge of the sun and eight on the west edge at hand in February, 1921,[2] the average value of the solar radiation was obtained for each day from 1 day before to 14 days after the appearance of faculæ on the east edge of the sun and for 13 days before and 2 days after the appearance of faculæ on the west edge. The means are given in Table XXX,

[2] *Nature,* Vol. 107, p. 108, London, March 24, 1921.

TABLE XXX

FACULÆ ON EAST LIMB OF SUN

	Before		*Days after*													
	1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Solar radiation	1.938	60	42	38	52	49	49	54	49	50	50	44	56	60	59	51

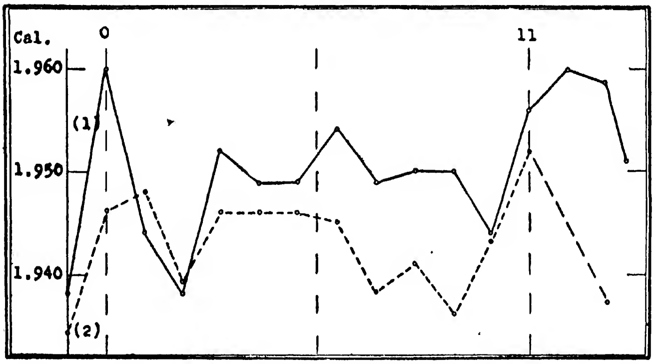
FACULÆ ON WEST LIMB OF SUN

	Days before														*After*	
	13	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2
Solar radiation....	1.958	44	56	58	49	56	56	56	55	48	51	46	54	62	..	47

and plotted in Fig. 224. The values for the west edge are plotted .010 calories lower than those for the east edge.

The plot shows that there was a sharp maximum of solar radiation on the day on which faculæ were first seen (zero day) on the

FIG. 224



Mean values of Solar Radiation Associated with Faculæ on the Sun's Limb

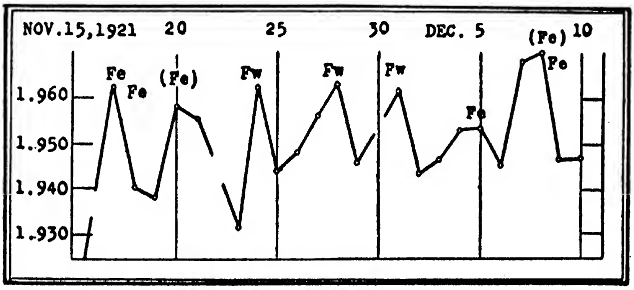
(1) Mean Solar Radiation One Day Before and Ten Days After Appearance of Faculæ on East Limb of Sun.

(2) Mean Solar Radiation 12 Days Before and One Day After Appearance of Faculæ on West Limb of Sun.

east limit of the sun, followed by another maximum of equal intensity 11 to 13 days later. There was also a sharp maximum of solar radiation when faculæ were first visible on the west limb of

the sun and a maximum 10 to 11 days earlier. This relation is confirmed by later observations from La Plata and also more recently by simultaneous observations at the Magnetic Observatory of Pilar, Cordoba. The solar observations are much interrupted by cloudy weather; but when they are complete day by day for a considerable interval, the relation between the variations in the intensity of solar radiation and the appearance of faculæ can be followed in detail as illustrated in Fig. 225. In this plot, the dots connected by lines show the day to day values of solar radiation observed at the Smithsonian Solar Physics Observatory near Calama, Chile, the letters *Fe* and *Fw* show the

FIG. 225



Solar Radiation Observed at Calama, Chile, Compared with Faculae Observed at La Plata, Argentina

dates when faculæ were observed on the east limb and the west limb of the sun, respectively, at La Plata and Pilar, Argentina. The letters in parentheses indicate that no faculæ were observed owing to cloudiness, but that faculæ were to be expected from preceding or subsequent observations. In two cases, November 18 and December 9, the faculæ continued to be bright after a decrease in solar radiation.

The explanation of the relation appears to be that the coming to the surface of heated gases on the limb of the sun where the radiation is normally diminished increases the intensity and area of the radiating surface of the sun and thus increases the total radiation. Abbot, Fowle, and Aldrich [3] had previously found that there is a relation between the total solar radiation and the

[3] Abbot, C. G., Fowle, F. E., and Aldrich, L. B.—"On the Distribution of Radiation over the Sun's Disk and New Evidences of the Solar Variability," *Smithsonian Miscellaneous Collection*, Vol. 66, No. 5.

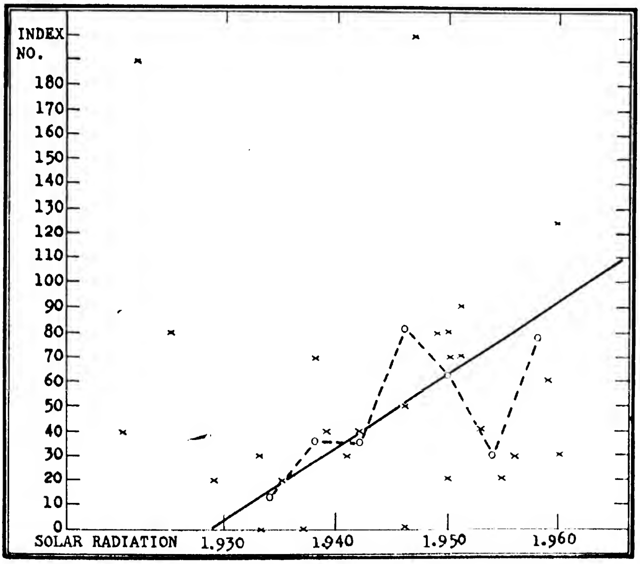
contrast of radiation between the edge and the center of the sun. In general, in the case of short period changes, the radiation was greatest when the contrast was least. Normally the heated interior of the sun is surrounded by cooler gases which have lost a considerable portion of their heat to space, and the intensity of the radiation coming from the surface of the sun diminishes from the center toward the edge of the sun. The measurements of the Smithsonian Astro-physical Observatory show that the decrease in the intensity of radiation toward the edge of the sun is greatest for short wave radiation and least for long-wave radiation, but is very considerable for each class of waves. For short waves the radiation is about 50 per cent less at a distance of 80° from the center (0.9 of radius) than in the center of the sun and about 25 per cent less for long waves.

It naturally follows that the total solar radiation is increased when heated gases like those which form faculæ come to the surface near the edge of the sun. A composite plot made of all the faculæ shows that their greatest visibility is between 70° and 80° from the center of the sun and their greatest influence on the solar radiation is in the same region and hence is proportional to their visibility. Taking the maximum effect as at 75° from the sun's center, a facula on the east edge, after producing its maximum effect, drifts westward with the sun's rotation, disappears from view as it approached the sun's center from lack of contrast of brightness and reappears again with a maximum of brightness at about 75° west of the sun's central meridian. As the period of rotation is about 27.2 days, the mean drift is 13.2° per day, so that to drift 150° from the east limb to the west limb would take 11.3 days, which no doubt explains the marked return of the maximum of solar radiation after about 11 days shown in Fig. 223. With the same speed of rotation, the faculæ would appear again on the east limb after 16 or 17 days, which probably explains the second maximum found at *C* in Fig. 223, although it appears to be somewhat later than the computed time in the case of the faculæ, but not in the case of the temperature change at Buenos Aires. The small change in solar radiation at the end of a complete rotation appears to indicate that before the end of 27 days, the faculæ have in general radiated away their excess of heat.

The relation of the faculæ to solar radiation was tested in another way by means of an index number derived from the product of the area and intensity of the faculæ. It was assumed that the greater the area of the facula as seen on the surface of the sun, the greater would be its effect in increasing the solar

radiation; also that the more brilliant faculæ would have a greater influence than less brilliant ones. The brilliancy at La Plata and Pilar is estimated on a scale of 3. One signifies faint, two moderately bright and three brighter than normal. An index number was prepared by estimating the area of the faculæ in degrees. This was easily done because the faculæ were drawn on charts on which lines of latitude and longitude were projected

Fig. 226



Relation of Solar Radiation to Area and Intensity of Faculæ

so that foreshortening near the edge was allowed for. An estimate of area was made by estimating the proportion of the ten degree square covered by the facula. The area was then multiplied by 0.5 if the facula was faint and by 2 if the facula was bright and remained unchanged if the brightness was normal. The indices thus obtained in cases when there were simultaneous observations of solar radiation were plotted on a dot diagram as illustrated in Fig. 226.

In this diagram the vertical numbers give the index numbers and the horizontal numbers give solar radiation values in gram calories per square centimeter. The crosses show the index values

corresponding with the observed solar radiation on the scale beneath. The small circles show the mean of groups of observation. Thus the mean index number for radiation values in steps of .004 is as follows: 1.928-32, 20; 1.932-36, 17; 1.936-40, 37; 1.940-44, 35; 1.944-48, 82; 1.948-52, 62; 1.952-56, 30; 1.956-60, 77.

These results have not been extended to include recent observations, but they indicate a relation between the visible area and the brightness of faculæ on the surface of the sun and the intensity of solar radiation. There are three or four observations which appear to have no relation with the solar radiation values, but the remainder indicate a straight line ratio which can be represented by the heavy line drawn through the dots. So far the observations of faculæ have been rough-eye estimate, it seems probable that if a more accurate measure were made of the visible contrast in brightness by means of a wedge photometer or a selenium cell an even better agreement would obtain.

From the observations plotted in Fig. 226, it seems that faculæ become visible to the eye when the solar radiation value is about 1.930 and at 1.950 cover an area of about 60 square degrees at normal intensity.

Returning to Fig. 225, there is found a remarkable regularity in the appearance of the maxima of radiation and in the appearance of faculæ. Maxima are found on November 17, 20–21, 24, 27–28, December 1, 4–5, and 7–8. The interval is almost exactly 3.5 days or two waves each week and it is of interest to note that a weekly period in the weather became so prominent in the weather of Argentina at that time as to attract popular attention and cause a discussion of the matter in the daily papers. If one follows the minor maxima *A*, *x*, *y*, *B*, *C*, etc., in the mean curve of solar radiation in Fig. 223 there is found the same rhythm of 3.5 days, there being eight maxima in the 28 days following the chief maximum *A*. Dr. Abbot[4] found evidence of the same rhythm in the solar maxima of 1916 and the Japanese meteorologist Sin-iti Kunitomi[5] has presented evidence of its relation to the weather in Japan.

The frequent recurrence of seven-day intervals between similar weather conditions in the United States has been a matter of comment by many writers and the author published a study of the subject in the *American Journal of Science*, 3d Series, Vol. 47,

[4] Abbot, C. G.—"On Periodicity in Solar Variation," *Smithsonian Miscellaneous Collection*, Vol. 69, No. 6.

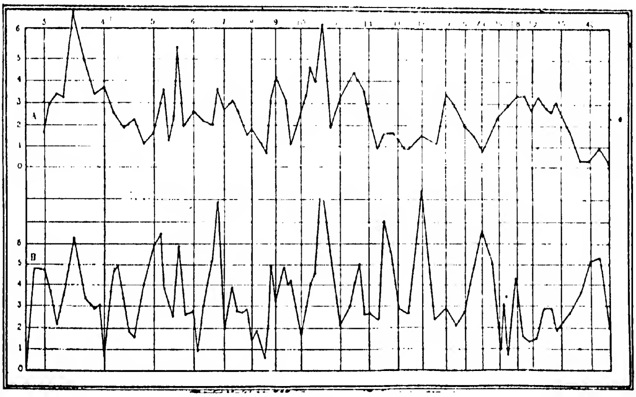
[5] *The Bulletin of the Central Meteorological Observatory of Japan*, Vol. III, No. 3, Tokyo, 1921, by Sin-iti Kunitomi, Hikotaro Tako.

p. 223, March, 1894, in which there was a suggestion of its solar origin.

Another method of studying possible periods in the solar radiation was by averaging the solar values in periods of different lengths running from 3 to 44 days and determining the amplitudes of the successive periods by harmonic analysis as suggested by Professor A. Schuster.

For this purpose two methods were tried, first, the mean solar radiation for each day up to 88 days following high values (1.990 +) was obtained from all the observations from 1909

FIG. 227



Periodogram of Solar Radiation

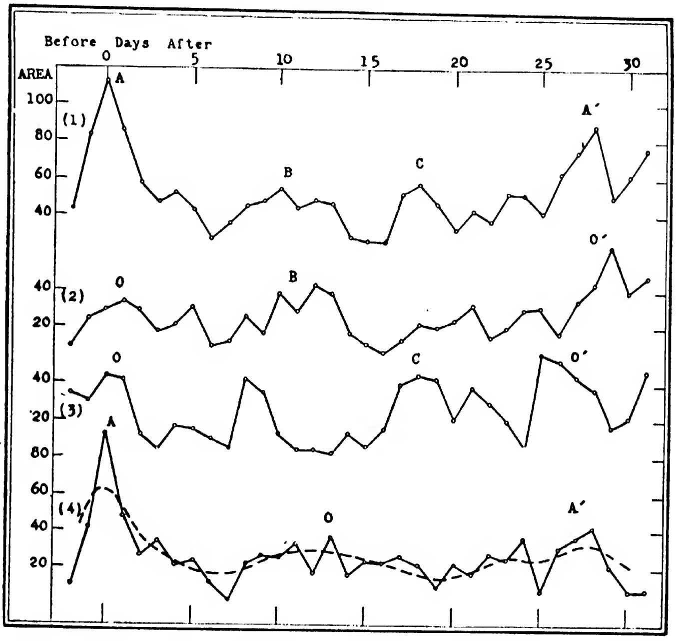
to 1918 and was then averaged in periods of different lengths. Second, all the observations made at Calama from July, 1918, to May, 1919, were averaged in periods in different lengths and the amplitudes determined by harmonic analysis.

The "periodograms" thus obtained are shown in Fig. 227. In this plot, the vertical figures give the amplitudes and the horizontal figures give the lengths of the periods in days plotted on a logarithmic scale. Maxima are found in both periodograms at 3.5, 5.6, 6.8, 9, 11 and 13 days indicating possible periods of these lengths. Except for the 11 day interval these periods could hardly be produced by solar rotation and if they are real, they are probably the result of some sort of harmonic action in the sun.

In order to ascertain whether there is any sort of regular sequence in the appearance of faculæ on the sun the observations

at La Plata during the year ending with July, 1921, were averaged in relation to maxima of faculæ in the same manner as were the *solar observations. There are three ways in which the matter may be approached. First, the total areas of all the faculæ observed on the surface of the sun may be obtained each day and*

FIG. 228



Mean Areas of Faculae Preceding and Following Observed Maxima of Faculae at La Plata, Argentina

(1) Mean Areas of Faculae Following Maxima Observed on Any Part of Sun.
(2) Mean Areas of Faculae on West Limb of Sun Following Maxima on East Limb.
(3) Mean Areas of Faculae on East Limb of Sun Following Maxima on West Limb.
(4) Mean Areas of Faculae Following Maxima in the Same Region of the Sun.

means obtained for 2 days before and 31 days after all the days in which the total area exceeded 70 square degrees. When treated in that way, the means give a curve represented by curve 1 in Fig. 228. This curve shows four distinct maxima, first, the maxima *A* on zero day; second, a maximum *B*, 10 to 12 days later; third, a maximum *C*, 17 to 18 days later, and fourth, a maximum *D*, 27 to 28 days later. These maxima were undoubtedly produced by

the solar rotation. The maximum B is produced by faculæ which first appeared on the east limb of the sun, became invisible when crossing the central area and again reach a maximum visibility 11 days later on the west limb. The maximum C is produced by faculæ which after being seen on the west limb reappear 17 to 18 days later on the east limb and the maximum D is the reappearance of the faculæ at the same place after a complete solar rotation, but with much diminished intensity. The number of cases was 24.

That B and C are the result of solar rotation may be made evident by a second method of treating the material. In this case, all the days were selected in which the area of faculæ on the east edge exceeded 60 square degrees and the mean of the areas observed on the opposite side of the sun were obtained for two days before and 31 days after the observation. A plot of these means is shown in curve 2, Fig. 228. This curve shows that a maximum B appeared on the west limb 10 to 12 days after the maximum on the east limb. The maxima observed on the west limb were selected and, in the same way as before, averages were formed for the areas observed on the east limb of the sun. These means are plotted in curve 3. Here no maximum is observed 10 to 12 days later but occurs at C, 17 to 19 days later, indicating that this is the interval required for the maxima observed on the west limb to reappear with maximum intensity on the east limb. There were only about ten cases considered in each case and a larger body of observations will be needed to give these intervals with greater precision.

In examining curves 2 and 3 another fact becomes evident, namely, when there was a maximum of faculæ on the east or the west limb there was simultaneously a maximum O of less intensity on the opposite limb of the sun. This maximum repeats itself at O' near the time of a solar rotation, the difference in the position of O' in the two cases being due to the fact that O is not exactly opposite A, but is somewhat displaced.

This fact indicates that there is something like a symmetrical arrangement of the faculæ on the surface of the sun itself.

In order to test this question, a third arrangement of the data was made. The maxima were arranged according to the side of the sun on which they were first observed and the mean of areas observed in the same part of the sun on successive days preceding and following was obtained for each day. In this way the conditions on the whole surface of the sun were observed as they unrolled themselves to the eye of the observer on the earth.

The means obtained in this manner are represented by curve 4 in Fig. 228. This curve shows that after the mean maximum A, a secondary maximum O' is seen 13 days later and a diminished maximum A' shows the return of the maximum A to the region where it was first observed.

Since 13 days is nearly half a solar rotation, the maximum at O is on the opposite side of the sun from A and this fact indicates that when a large outbreak of faculæ occurs on one side of the sun, there is a simultaneous outbreak on the opposite side like the tidal wave produced in the oceans of the earth by the moon.

This tidal-like effect, if true, would cause an additional periodicity in the faculæ, as seen from the earth, of a nature entirely different from that due solely to the rotation of the sun. This seems a question of such importance as to be worthy of full investigation and a rich store of data was found in the careful and detailed observations of faculæ made by Professor A. Wolfer [6] in Zurich during an entire sunspot period. By taking the mean rotation of the sun in the region of the sunspots and counting time from a fixed epoch, Wolfer was able to record each outbreak of faculæ in its proper position on the sun's surface in latitude and longitude, thus permitting a study of the distribution of faculæ on the sun's surface independent of its rotation. For the purpose of comparing the results with those already given here, it seemed best to divide the surface of the sun into 27 zones corresponding to the amount of rotation in a day rather than in zones of 10° as used by Wolfer.

Using the charts prepared by him and the position of the central meridian on each date, as given, the area covered by faculæ was estimated within the ten degree zone passing through the central meridian of the sun on each date. The faculæ are represented in Wolfer's diagrams by elongated spots or splashes and only the area of these splashes was estimated, omitting the intervening blank spaces.

With the assistance of William Hoxmark, the data were read for an interval of seven years including the minimum sunspot year 1889 and the maximum year 1893.

Following the system used in the case of the solar radiation values, all the zones were selected within which there was a maximum of faculæ and in which the area covered equalled or exceeded 50 square degrees. Then averages were obtained for

[6] *Publikationen der Sternwarte des Eidg. Polytechnikums zu Zurich,* Bands I, II, III, herausgegeben von A. Wolfer, Professor der Astronomie und Direktor der Sternwarte.

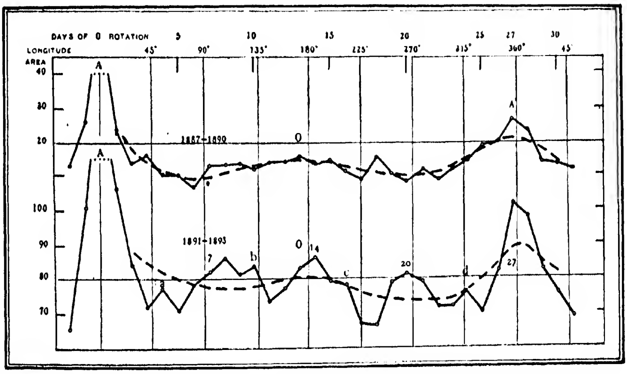
the areas corresponding to 2 days earlier and 31 days later calling a difference in longitude of 13.3° equal to 1 day.

The mean results are given in Table XXXI for each year. Means were also obtained for the group of years 1887–1890 covering sunspot minimum, and the group of years 1891–1892 covering sunspot maximum as well as the mean of the seven years.

The results for sunspot minimum and sunspot maximum are plotted in Fig. 229 in the same form as curve 4 in Fig. 228.

The maximum thirteen days later and hence on the opposite side of the sun from the principal maximum is clearly visible in

FIG. 229



Mean Distribution of Faculae in Longitude on Sun Following Marked Outbreaks of Faculae

the curve for sunspot minimum, 1887–1890, while on the curve for sunspot maximum there are four distinct maxima following at intervals of seven days. This regularity suggests a harmonic vibration of the sun's mass as is seen by plotting the results in a different way as shown in Fig. 230.

In this figure the circles indicate sections passing through the equator of the sun and the plotted lines show the areas of faculæ at different longitudes accompanying large outbreaks of faculæ at the upper part of the circle marked zero or 27 days. The maxima at the top of the circles are not the primary maxima but the maxima observed 27 days later. At the time of sunspot maximum, it is seen that there is not only a maximum opposite to the chief maximum, but there are also maxima at right angles to the

TABLE XXXI

MEANS OF THE AREAS OF FACULÆ PRECEDING AND FOLLOWING MAXIMA OF FACULÆ AS OBSERVED BY WOLFER

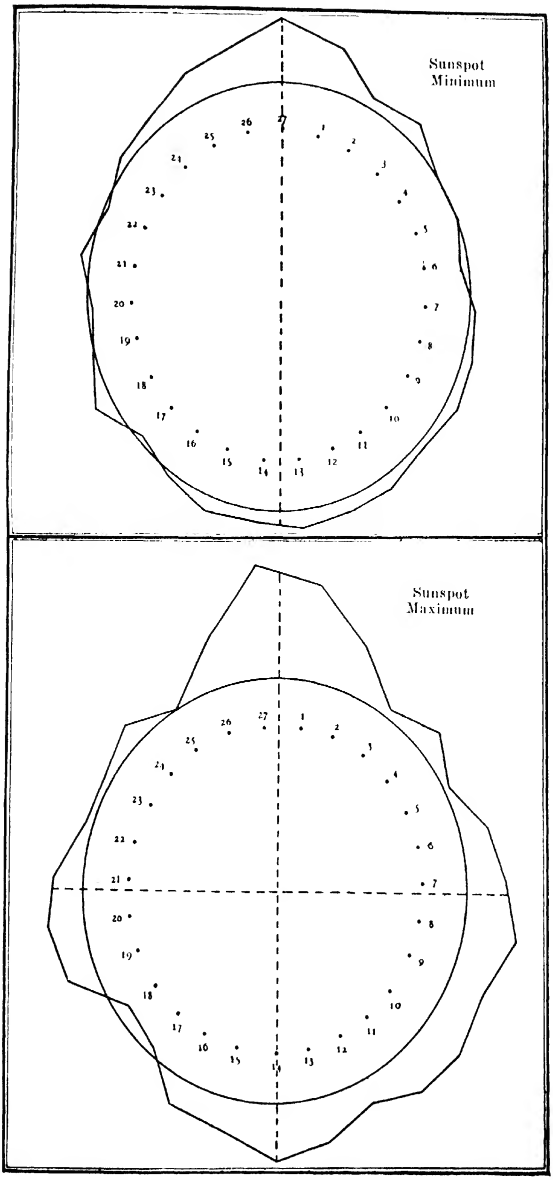
	Days before		Days after															
	2	1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1887.....	12	27	65	24	14	26	10	10	10	17	13	9	10	20	28	15	10	20
1888.....	21	28	64	24	15	14	10	13	10	10	15	15	9	12	13	19	14	11
1889.....	3	20	60	19	5	11	11	9	4	10	7	6	10	10	7	10	17	10
1890.....	15	30	78	29	18	14	10	7	5	14	16	26	18	12	8	14	9	15
1891.....	34	54	105	46	41	35	33	37	32	32	41	38	44	24	27	32	40	29
1892.....	40	75	157	92	63	49	70	54	69	77	63	64	67	63	68	74	72	63
1893.....	120	175	248	184	147	131	129	121	134	137	153	142	142	131	135	144	147	145

	Days after															
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1887	13	11	11	10	15	14	7	14	21	17	19	33	27	13	17	14
1888	9	10	11	9	8	13	12	12	13	23	31	20	18	16	16	6
1889	3	6	16	5	6	11	13	12	4	5	13	28	19	6	9	14
1890	20	9	22	15	1	8	10	10	17	28	18	28	27	19	9	14
1891	27	32	25	39	45	40	34	28	31	36	34	61	58	39	34	26
1892	71	59	64	54	51	55	60	58	68	49	70	77	19	57	56	55
1893	137	111	108	145	146	143	123	131	129	126	142	168	156	149	134	125

chief maximum and indications of smaller maxima marked *a*, *b*, *c*, *d* in Fig. 229 which are nearly one eighth part of the circle from the larger maxima and would give a period of about 3.5 days when the time of the solar meridians passing a line joining the sun and earth is considered. It will be noticed, however, in Fig. 230 that the secondary maxima at the time of sunspot maximum are not exactly at right angles to each other, but are on the side of the horizontal line away from the chief maximum indicating that the third harmonic of 120° or 9 days also contributes to producing the distribution found. These different harmonics vary in intensity from time to time and will well repay further study. They furnish a rational explanation of the 3.5, 5.6, 6.8, 9 and 13 day maxima shown by the periodograms of solar radiation in Fig. 227, as these periods are approximately one eighth, one fifth, one fourth, one third and one half of a solar rotation as seen from the earth. On the other hand, the 11 and 18 day maxima have nothing to do with vibrations of the sun's mass, but arise solely from the maxima of faculæ moving from the most favorable position for influencing solar radiation on one limb of the sun to the most favorable position on the other limb, as illustrated in Fig. 224.

Wolfer discussed his material in a different way. Representing his observations graphically rotation by rotation by assuming a

Fig. 230



Showing Distribution of Faculae Around the Sun Following Marked Outbreaks of Faculae

mean synodic rotation period of 27.28 days and reckoning from a fixed epoch, he found that there was a marked tendency for the faculæ and spots to form in certain definite regions on nearly opposite sides of the sun for long intervals at a time as if there were more or less permanent weaknesses in the sun's envelope or else that there are stresses in the solar envelope produced by the tidal action of the earth.

Outside of the solar rotation periods, there is generally recognized to be a well developed but somewhat irregular period of about 11 years in the amount of sunspots. Professor A. Schuster[7] made an investigation as to the possibility of other periods in the spots and found other possible periods of less intensity of about 4.8 years, 8.3 years and 13.6 years. Using the "periodogram" method of Schuster an investigation of possible shorter periods was made by Elsa Freknel.[8]

Her results show possible periods of about 200 and 68.5 days.

THE SUNSPOT PERIOD OF ELEVEN YEARS

The question of the relation of the weather to the eleven-year sunspot period has been a question of a great deal of investigation, but the complication of the effect has led to much confusion and disbelief. The only generally accepted result is that found by Köppen and confirmed by Nordmann, Newcomb and others, that the world's mean temperature is somewhat lower at the time of sunspot maximum than at the time of minimum, an effect which is especially marked in the tropical belt of the world.

Walker's researches show that there are certain regions of the earth where the reverse is found although for the earth as a whole, the surface temperature is undoubtedly lower at the time of maximum sunspots.

This result appears puzzling in view of the fact that the measurements of the Smithsonian Astro-physical Observatory show a maximum of radiant energy at the time of the maximum of sunspots, see Fig. 214, and has given rise to many divergent views and explanations. Its most probable explanation is that it is a surface phenomenon caused by the increased rainfall, increased cloudiness and increased circulation in the tropics and by the surface cooling due to increased radiation from the ground

[7] *The Astronomical Journal,* Vol. 23, No. 2, March, 1906, p. 101.

[8] Untersuchung über Kurzperiodische Schwankungen der Häufigkeit der Sonnenflecken—*Publikationen der Sternwarte des Eidg. Polytechnikums zu Zurich,* Bd. V, p. 47.

in middle latitudes (30° to 60°) in winter where the increased pressure and decreased rainfall indicate decreased cloudiness.

A comparison of the difference of pressure between the time of maximum sunspots and the time of minimum sunspots in accordance with the plan illustrated in Table XXVII shows that throughout the whole of the tropical belt, the pressure is lower at the time of maximum sunspots than at the time of minimum spots.

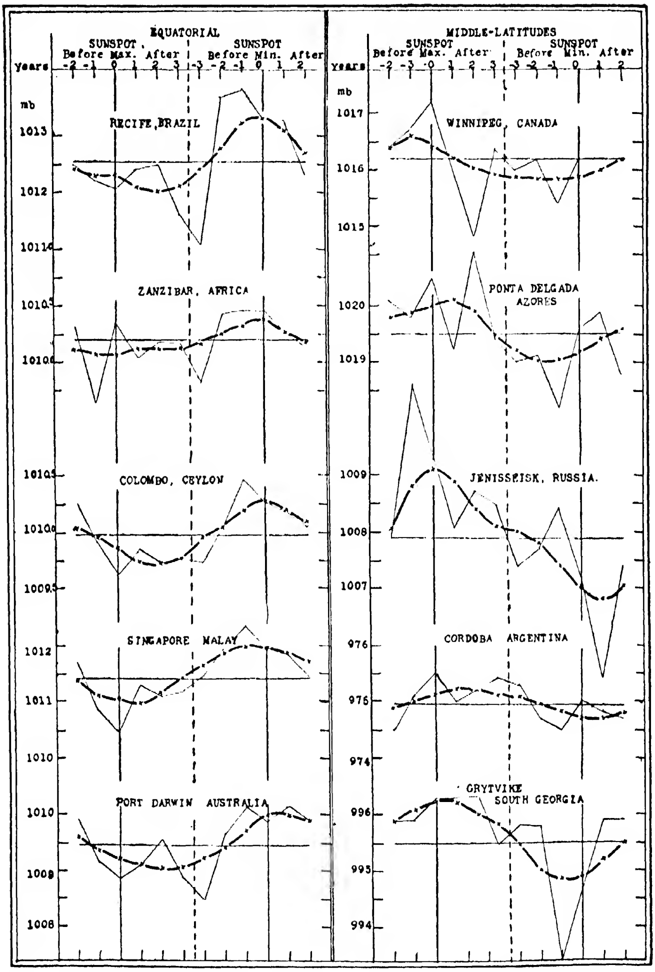
In Fig. 231, plots of pressure are given for a number of stations within the tropics and for other stations in middle latitudes. The light line shows plots of the mean pressure for each year from two years before to three years after sunspot maximum and from three years before to two years after sunspot minimum and the heavy lines show smoothed means of four and then of two successive values.

The plots of the unsmoothed means show that there are various maxima and minima of pressure between sunspot maximum and sunspot minimum. One minimum occurs in the tropics near sunspot maximum, another about four years later and a third about two years after sunspot minimum. There are secondary maxima about two years before and two years after sunspot maximum and a chief maximum about one year before sunspot minimum. This greater variability might be expected, because the meteorological changes do not follow the sunspots but follow changes of solar radiation which are more variable than sunspots (see Figs. 212 and 214), but whether these variations arise from variations in solar radiation which have some definite relation to the sunspot period or whether they are accidental variations resulting from the shortness of the period, mostly 1870–1917, only time can tell.

The curves plotted in heavy lines from smoothed means of four and two years show a maximum of pressure at sunspot minimum and a minimum of pressure near sunspot maximum. There appears to be a lag in the effect at sunspot maximum amounting at most places to one or two years.

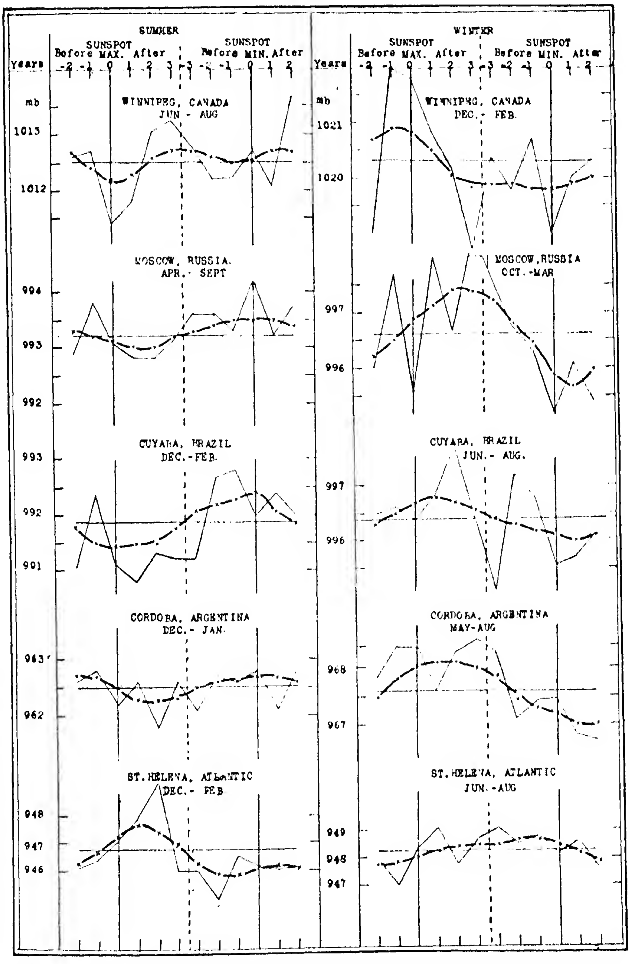
At stations in latitudes 30° to 50° the conditions are reversed, the highest pressure occurs near sunspot maximum and the lowest near sunspot minimum as will be seen from the curves for selected stations in middle latitudes. The minor oscillations are not so clearly related to each other as within the tropics, but in general there is a maximum of pressure at sunspot maximum and a minimum of pressure one year before sunspot minimum. The chief exception is at Jenisseisk, Russia, but other stations like Ekater-

Fig. 231



Mean Pressure for Each Year of Sunspot Period Showing Opposite Trend of Pressure during Sunspot Period in the Equatorial Belt and in Middle Latitudes for the Year. Heavy Lines are from Means of 4 and 2

FIG. 232



Mean Pressure for Each Year of Sunspot Period Showing Opposite Trend of Pressure over Continents and Oceans in Summer Compared with Winter

inburg show a maxima and minima more nearly corresponding to those at Cordoba. Winnipeg shows a minimum pressure two years after sunspot maximum but other stations in Canada, as Toronto and Montreal, show the chief minimum near sunspot minimum.

In the mean for the year stations in the north Atlantic and north Pacific like Stykkisholm and Nome show changes of pressure similar to those in the tropics with the maximum of pressure at sunspot minimum. The annual mean values at stations at the southern ends of the continents, in the southern hemisphere like Punta Arenas, Chile, Cape Town, Africa, and Adelaide, Australia, show a relation to the sunspot curve similar to the tropical stations. But when these changes in high latitudes are followed month by month the relation to the sunspots is found to change from direct to inverse at least twice a year, as will be seen later, see Fig. 236.

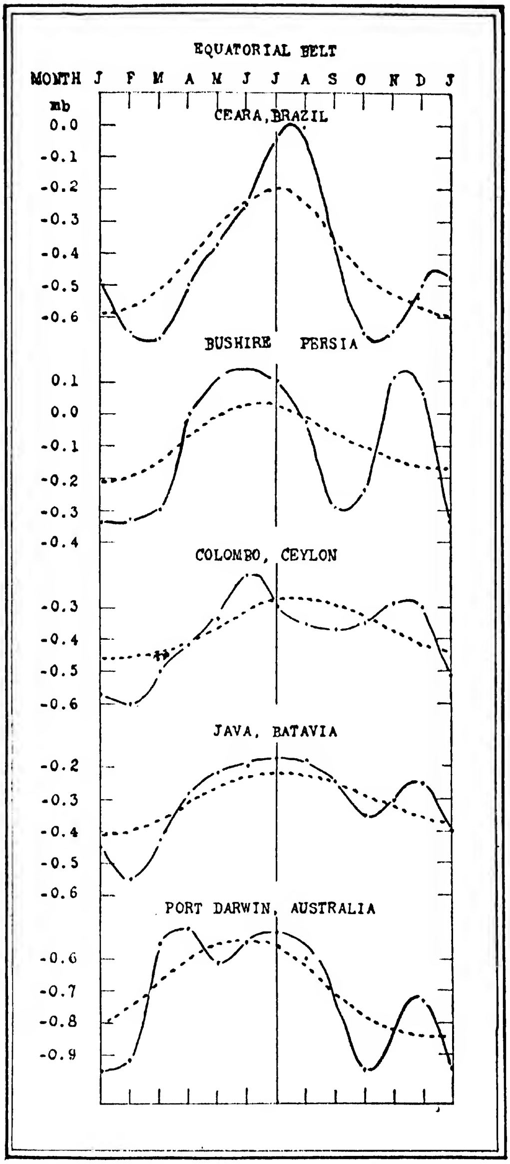
Within the tropics the pressure follows the inverse relation to the sunspots throughout the year, but in middle latitudes there is a change in the relation between summer and winter. In summer, the trend of the pressure over the continental areas is the same as in the tropics; while over the oceans, the trend is inverse to the equatorial belt. In winter the pressure is higher over the continents at sunspot maximum than at sunspot minimum, and there is an inverse relation over the oceans.

These contrasts are shown in Fig. 232, in which the lighter lines are plotted from the mean pressure for the years of maximum and minimum sunspots and for two to three years preceding and following, and the heavy lines are plotted from the smoothed means of four and two successive years.

In order to study the annual change in the influence of the sunspots, the pressures were averaged month by month for each month of the year. Means were obtained for the years of maximum and minimum sunspots and for the two or three years preceding and following according to the scheme presented in Table XXVII. Then means of four and two were obtained from the five mean values at sunspot maximum; and for two years before and for two years after; also in the same way for sunspot minimum. The differences show whether the mean pressure is higher or lower around sunspot maximum than around sunspot minimum.

Owing to the short periods of observations at many stations the differences from month to month were irregular at many stations

FIG. 233



Yearly Period in the Difference of Pressure between Maximum and Minimum Sunspots in the Equatorial Belt

and to bring out the annual period, a further smoothing of the monthly differences was made by the formula $\frac{a + 2b + c}{4}$.

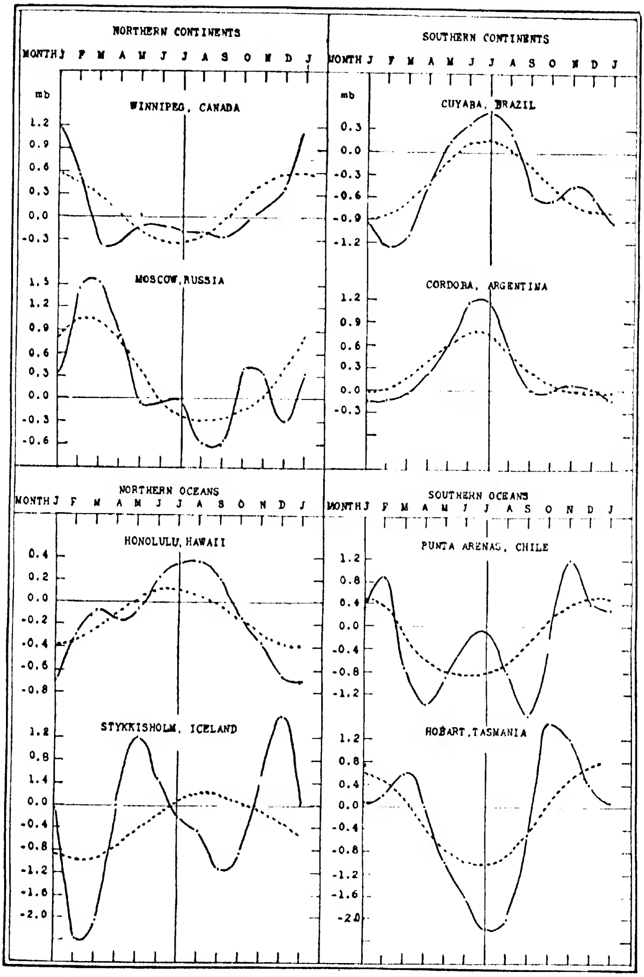
The results from a few selected stations within the equatorial belt are plotted in Fig. 233. These plots show clearly a tendency for a yearly and a half-yearly period. The yearly period is shown by the broken curve drawn through the plots and the half-yearly period by the oscillations on each side of this mean curve.

It is seen from the plots that the annual period is the same on both sides of the equator from Bushire in Persia to Fort Darwin in northern Australia and is the same in the Indian Ocean as in Brazil. The semiannual period shows maxima near the solstices (June and December) at all the stations.

Similar plots for extra-tropical stations are shown in Fig. 234. The annual trend as indicated by the broken lines is the reverse over the continents to that over the oceans and the annual trends for similar conditions in the two hemispheres are inverted to each other as might be anticipated because the seasons are inverted. In each case when the number of sunspots is greater, the tendency is for the pressure to be high over the continents in winter and over the oceans in summer. That the air flowing out of the equatorial belt at sunspot maximum when the solar radiation is greater should pile up on the cold continents in winter and on the cool oceans in summer is what might be expected from the laws of physics, but the reason of the annual period within the tropics is not so evident. One suggestion is that the sun is nearer the earth in December than in June and that an increase of solar radiation produces a greater effect in December. This is probably true, but the observed effect is greater than would be anticipated. The mean depression of the barometer from sunspot minimum to sunspot maximum is only about 0.4 millibars and the annual range is about 0.2 millibars when according to computation the range ought to be only about 7 per cent of the mean effect or about 0.03 millibars. The annual period in the tropics arises perhaps from the much greater mass of land in the northern than in the southern hemisphere, so that the increased expansion of the air over the northern continents in June to August when the sun is hotter than normal causes a part of the expanded air to enter the equatorial belt.

In Fig. 235 the analyzed results for 82 stations scattered over the globe are shown on charts. The monthly differences of pressure between maximum and minimum of sunspots were analyzed

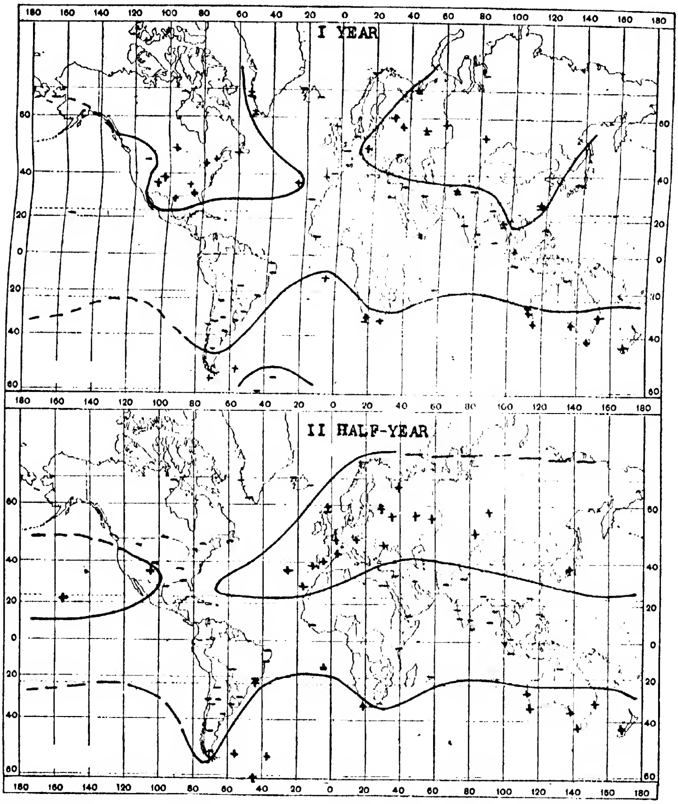
FIG. 234



Yearly Period in the Differences Derived from the Pressure at Sunspot Maximum Minus the Pressure at Sunspot Minimum from Smoothed Means of 4 and 2 Years for Each Month Showing an Inversion in the Yearly Period between Continent and Ocean and between the Two Hemispheres. Dotted Lines Show the Annual Period, Superposed on Which is a Half Year Period. The Combination of the Two Gives the Observed Values Plotted in the Continuous Curves.

first graphically and then by harmonic analysis into annual and semiannual periods. The areas with + signs in Chart I show the regions where the pressure was higher in January than in July as indicated by the smoothed curves of monthly differences

Fig. 235



Distribution of the Maxima and Minima of the Yearly and Half-yearly Periods under the Influence of Sunspots

in pressure between the maximum and the minimum of sunspots. (See broken curves in Fig. 234.)

The areas with + signs in Chart II show where the pressure is higher at the equinoxes than at the solstices as determined from the monthly differences in pressure between the maximum

and minimum of sunspots, while the — signs show the regions where this semiannual period was the reverse.

Chart I in Fig. 235 shows that when sunspots increase there is an annual change in the effect so that the pressure is lower in January than in July within the tropics and also over the north Atlantic and north Pacific, while it is higher in January than in July over the north American and Eurasian continents and at latitudes about 40° S.

Chart II shows that when sunspots increase there is also a semiannual change in the effect so that the pressure is lower in the equatorial belt at the equinoxes than at the solstices and higher at latitudes 40° to 50° north and south of the equator. It is also lower at the equinoxes than at the solstices in Ireland and Greenland as well as in Canada and a large part of the United States. It is probably lower at the equinoxes than at the solstices at high southern latitudes, but there are no data from which it can be determined. The half-year period with increased sunspots is believed to be an intensification of the normal half-year period in pressure illustrated in Chapter III.

The great intensification of this period in high latitudes with increased sunspots is, however, surprising. Also the reason is not evident for the difference in phase between the two sides of the north Atlantic, and for North America and Europe.

In the northern Atlantic and in northern Europe the half-yearly change in pressure attending increased sunspots is greater than the yearly change and there is a marked seesaw of pressure between Ireland and western Europe as illustrated by Fig. 236.

In Petrograd, Russia, with increased sunspots, the pressure is high in February and March and low in May and June. It is high again in September and October and low in December. The reverse is true for Stykkisholm, Iceland.

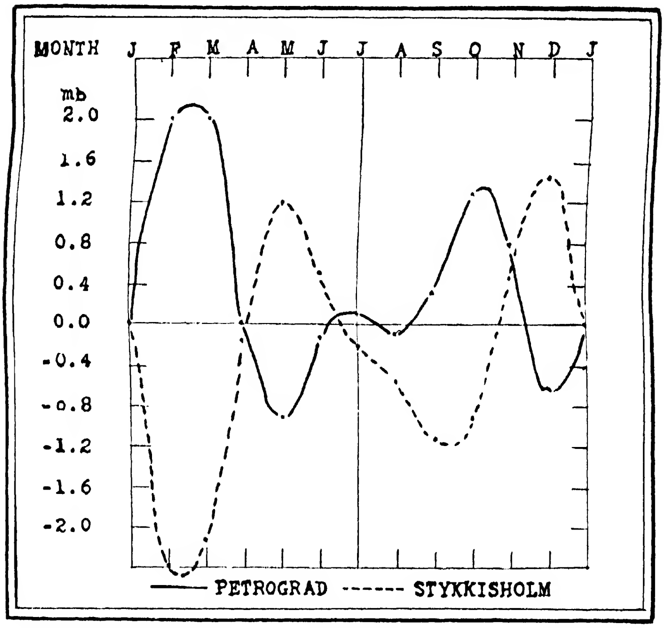
The half-yearly change of pressure with increased sunspots is also very large in high southern latitudes, as is shown by the plots for Punta Arenas and Hobart in Fig. 234.

RELATION OF THE SUNSPOT PERIOD TO RAINFALL

The rainfall data from 110 stations scattered over the world were compared with the sunspots in the same way as the pressure, using the formula given in Table XXVII. The general results of the differences of rainfall between the time of sunspot maximum and sunspot minimum are given in Fig. 216. In Fig. 237, the rainfall data are plotted for a number of selected

stations in the tropics and in middle latitudes for each year of the sunspot period beginning two years before sunspot maximum and ending two years after sunspot minimum. Within the tropics the rainfall is generally higher at sunspot maximum than at sunspot minimum, but in a small percentage of the cases this condition was reversed, apparently owing to local conditions or to

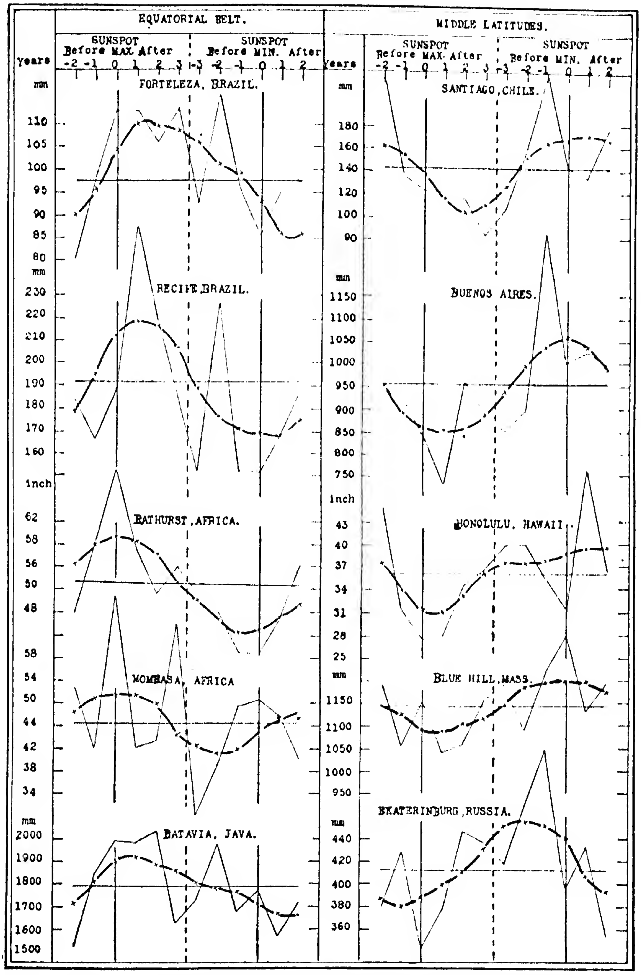
FIG. 236



See-saw of Pressure between Petrograd and Stykkisholm in Sunspot Period

the direction of the prevailing winds from adjacent regions of high pressure. In middle latitudes the condition is reversed, except in the region of the north Atlantic as at Thorshavn and the north Pacific as at Victoria, B. C., where the rainfall like the pressure follows the same trend as in the tropics. This is true also for the region of maximum rainfall in southern Chile, for the region of Cape Town and Durban on the south coast of Africa, and in southern Australia as at Melbourne and Hobart. Also at continental stations, like Denver in the dry region of the United States, and at Mendoza in the dry region of Argentina,

Fig. 237



Mean Rainfall for Each Year of the Sunspot Period Showing Trend of the Yearly Rainfall Near the Equator to be the Same as That of the Sunspots and in the Opposite Direction in Middle Latitudes

TABLE XXXII

EXCESS OR DEFECT OF RAINFALL AT SUNSPOT MAXIMUM COMPARED WITH SUNSPOT MINIMUM.

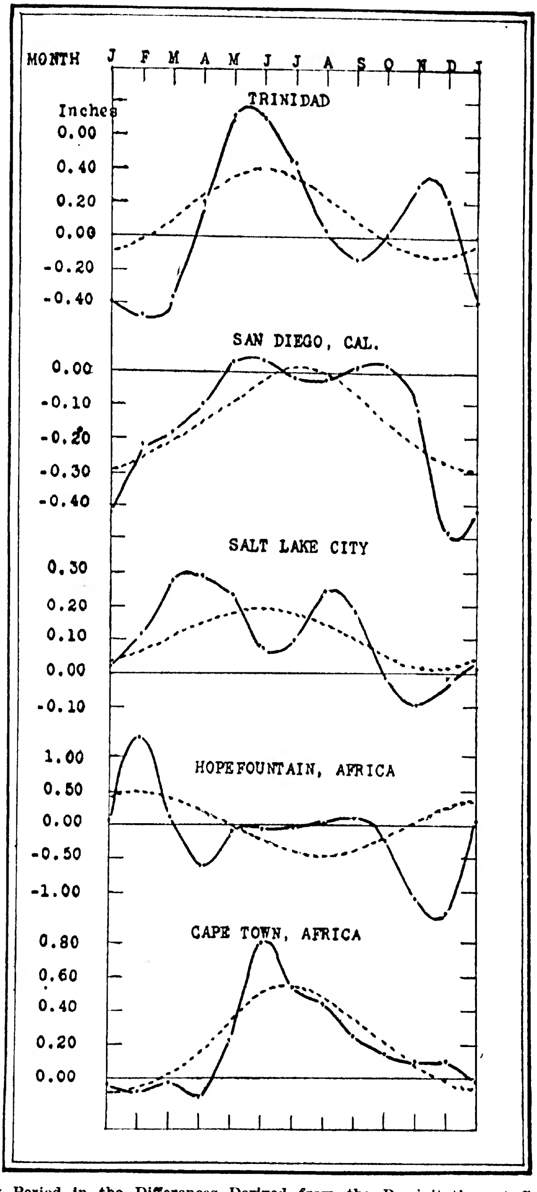
Stations	Trinidad	Madras	Central India	Hong Kong
Latitude *Longitude* *Years*	10° 35′ N. 61° 30′ W. 1862-1914	13° 4′ N. 80° 14′ E. 1813-1900	— — — — 1841-1908	22° 18′ N. 114° 10′ E. 1884-1918
Wet Season Excess or Defect *Months*	+ 14.56 in. + 12% May-Sept.	+ 31.83 in. + 26% May-Nov.	+ 11.58 in. + 9% June-Oct.	+ 14.23 in. + 9% June-Sept.
Dry Season Excess or Defect *Months*	— 6.62 in. — 24% Jan.-Apr.	— 0.07 in. — 3% Dec.-Apr.	— 0.15 in. — 3% Mar.-May	— 7.59 in. — 51% Nov.-Feb.

Stations	San Diego	Mendoza	Hopefountain
Latitude *Longitude* *Years*	32° 43′ N. 117° 10′ W. 1850-1901	32° 53′ S. 68° 49′ W. 1869-1918	20° 15′ S. 28° 40′ E. 1888-1906
Wet Season Excess or Defect *Months*	— 4.96 in. — 20% Nov.-Mar.	+ 2.00 in. + 12% Oct.-Mar.	— 4.66 in. — 52% Oct.-Dec.
Dry Season Excess or Defect *Months*	+ 0.59 in. + 19% May-Oct.	— 2.56 in. — 43% Apr.-Sept.	+ 0.14 in. + 35% July-Sept.

where summer rains decidedly predominate over winter rains, the trend of the annual rainfall in the sunspot period is the same as that of the tropics.

In general, where there is a marked wet and dry season in any part of the world, the relation of the rainfall to the sunspots is reversed for the two seasons. If in one season the rainfall is higher at the maximum of sunspots, in the other season it will be lower. This effect is illustrated in Table XXXII, in which is given the excess or deficiency of rainfall for the three years at sunspot maximum as compared with the three years at sunspot minimum. The excess or defect is given in inches and in percentages of the mean rainfall. The three years include the year of maximum or minimum, one year before and one year after.

FIG. 238



Yearly Period in the Differences Derived from the Precipitation at Sunspot Maximum Minus the Precipitation at Sunspot Minimum

In Fig. 238 the differences of rainfall between maximum and minimum of sunspots are plotted month by month for a number of selected stations. The means of four and two years during sunspot minimum including the two years before and two years after minimum, are subtracted from the means of four and two years at sunspot maximum. Before plotting these differences, they were further smoothed by the formula $\frac{a + 2b + c}{4}$. The stations in both hemispheres show an annual and a double annual period as in the case of the pressure. Interior continental stations in middle latitudes like Salt Lake City in the United States and Hopefountain in southern Africa show a maximum rainfall with increased sunspots in summer and a minimum in winter (the seasons being reversed in the two hemispheres), while certain coast stations like Cape Town, and the stations on the Pacific coast of British Columbia and of southern Chile (40°–50° S.), and the stations on the southern coast of Australia and in New Zealand show a maximum rainfall in winter with increased sunspots.

The half-yearly period in rainfall has not been worked out in detail, but is clearly related to the half-yearly period in pressure, since the maxima tend to occur at the equinoxes and solstices and probably, in general, are the reverse of the pressure changes.

AIR TEMPERATURE AND SUNSPOTS

For a study of the relation of the temperature of the air to sunspots, Dr. Köppen [9] collected data from all available sources in the world and from the mass of data thus assembled he showed that the mean temperature of the surface air over the globe was lower at sunspot maximum than at sunspot minimum. He further showed that this held true within the tropics as well as in the extra-tropics both north and south of the equator. His results have been confirmed by a number of independent investigators and are now generally accepted.

The upper three curves in Fig. 239 show plots of his data treated in the same way as were the pressures and rainfalls previously given. The data cover the interval from 1804 to 1910 for the equatorial and the north temperate zone and from 1841 to 1908 for the south temperate zone. Curves are plotted for each zone giving the yearly means and also smoothed means of 4 and 2 years in heavy lines. It is seen that in every zone the

[9] Köppen, W.—Lufttemperaturen, Sonnenflecken und Vulkanausbrüche, *Meteorol. Zeitschr.*, July, 1914, Vol. 31, pp. 305-308.

TABLE XXXIII

Mean Temperatures During the Sunspot Period in Tropical and Subtropical Regions Where the Rainfall is Light or Where There is Less Rainfall at Maximum than at Minimum Sunspots.

Stations	*Years*	*Sunspot Maximum*					
		Years Before		*Max.*	*Years After*		
		−2	−1	0	+1	+2	+3
		° C.	° C.	° C.	° C.	° C.	° C.
Algiers, Algeria	1888-1911	18.9	19.2	18.9	18.8	19.1	18.6
Aden, Arabia	1882-1913	28.3	28.2	27.9	28.2	28.3	28.5
Alice Springs *	1879-1913	20.6	21.2	21.7	20.8	20.0	21.0
Galveston, U.S.	1871-1916	20.8	20.9	21.0	21.2	20.6	20.6
Goya, Argentina	1877-1917	20.6	20.4	20.8	20.5	20.3	20.4
Mean....................		21.84	21.98	**22.06**	21.90	21.72	21.82
Smoothed mean of 5......		21.86	21.90	**21.90**	21.90	21.84	21.83

Stations	*Years*	*Sunspot Minimum*					
		Years Before		*Min.*	*Years After*		
		−2	−1	0	+1	+2	+3
		° C.	° C.	° C.	° C.	° C.	° C.
Algiers, Algeria	1888-1911	18.7	19.7	19.0	18.5	18.6	18.7
Aden, Arabia	1882-1913	28.4	28.2	28.3	28.3	27.7	27.9
Alice Springs *	1879-1913	20.9	20.9	21.4	21.1	20.9	20.9
Galveston, U.S.	1871-1916	20.4	20.9	20.5	20.7	21.0	20.6
Goya, Argentina	1877-1917	20.2	20.2	20.5	20.6	20.4	20.4
Mean....................		21.72	21.98	21.94	21.84	21.72	21.70
Smoothed mean of 5.....		21.84	21.86	21.84	21.83	21.81	21.81

* Australia.

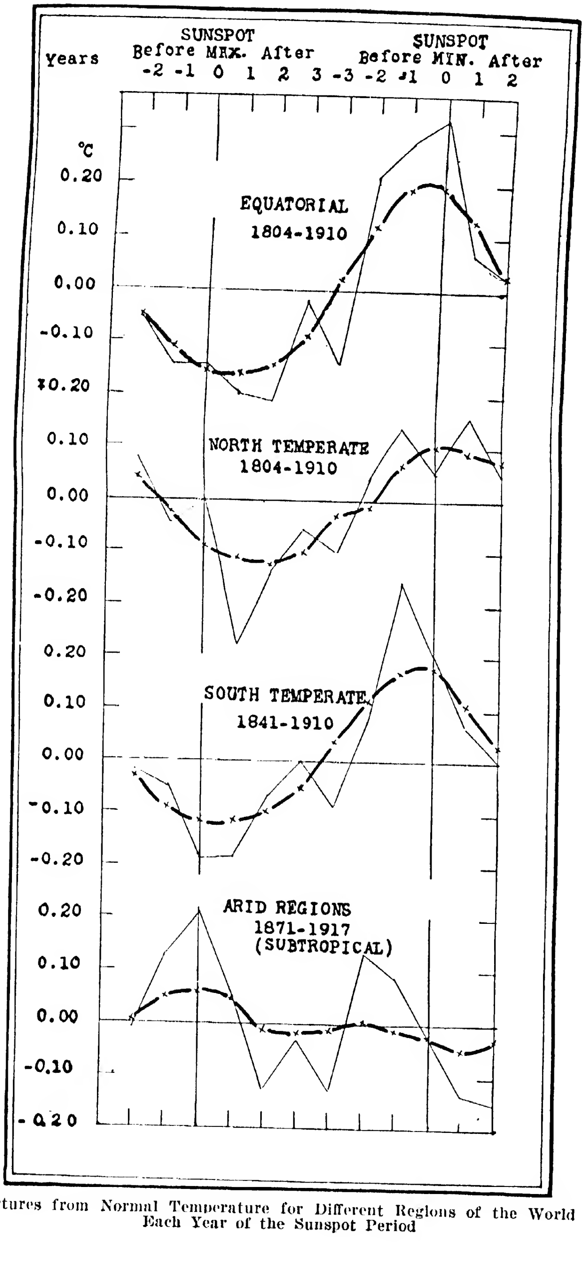
surface temperatures are lower at maximum sunspots than at minimum, although there is a tendency for a lag in effect at the time of maximum sunspots as is seen in the curves of pressure and rainfall previously given.

When the data for the most arid regions of the tropical and subtropical regions are studied, however, it is discovered that the temperature is not lower at maximum than at minimum sunspots, but is in fact a little higher. The same is true at many subtropical stations where the rainfall is less at maximum than at minimum sunspots.

The results are shown in Table XXXIII for five widely separated regions.

In Algiers, in Aden, and in Alice Springs, central Australia, the rainfall is light, while at Galveston and Goya the

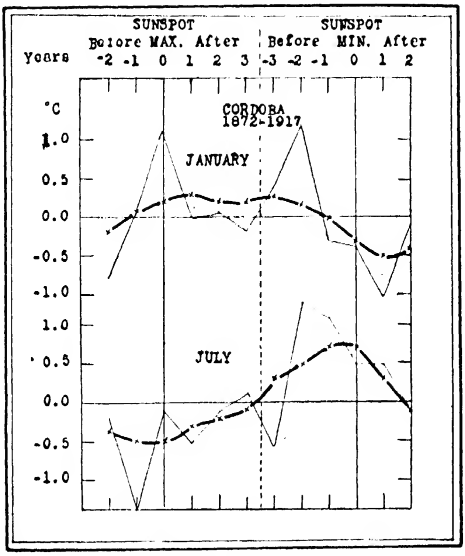
FIG. 239



Departures from Normal Temperature for Different Regions of the World for Each Year of the Sunspot Period

rainfall is less at maximum than at minimum sunspots. The lowest curve in Fig. 239 shows a plot of these values on the same scale as the results of Dr. Köppen. This curve is inverse to the others and indicates that rainfall is an important element in determining the inversion of the surface temperature to the sunspots in tropical and subtropical regions. Without the rainfall the temperature would probably be generally higher in the tropics

FIG. 240



Departures from Normal Temperature at Cordoba, Argentina, for January and July for Each Year of the Sunspot Period

at maximum than at minimum sunspots, although increased atmospheric circulation must also tend to lower surface temperatures in the tropics at the time of maximum sunspots.

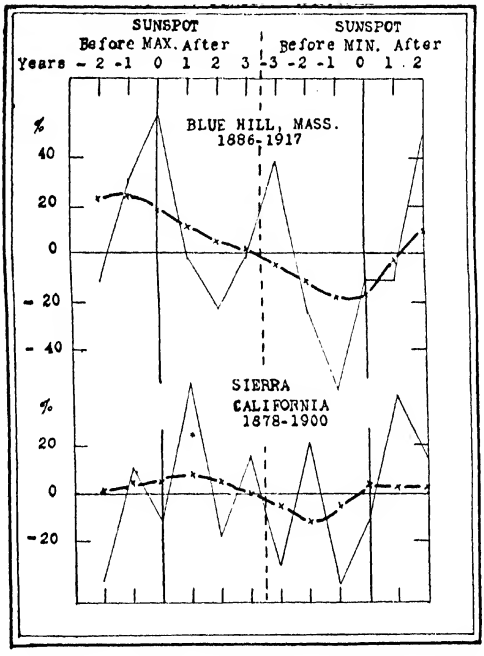
Another interesting fact is that at certain interior continental stations in middle latitudes of which Cordoba in Argentina is an example, a maximum of temperature occurs, with the maximum of sunspots in summer, and the relation is reversed in winter. This relation is shown by the two curves in Fig. 240, in which the upper curve shows the mean temperature in January (midsummer) for each year of the sunspot period and the lower curve for

July (midwinter). At Cordoba there is no marked correlation of the summer rains with the sunspots.

RELATION OF SNOWFALL AND ICEBERGS TO SUNSPOTS

Fig. 241 shows the amount of snowfall for each year of the sunspot period for two stations in the United States. The smoothed curve of the snowfall at Blue Hill, Massachusetts,

FIG. 241



Amount of Snowfall for Each Year of Sunspot Period

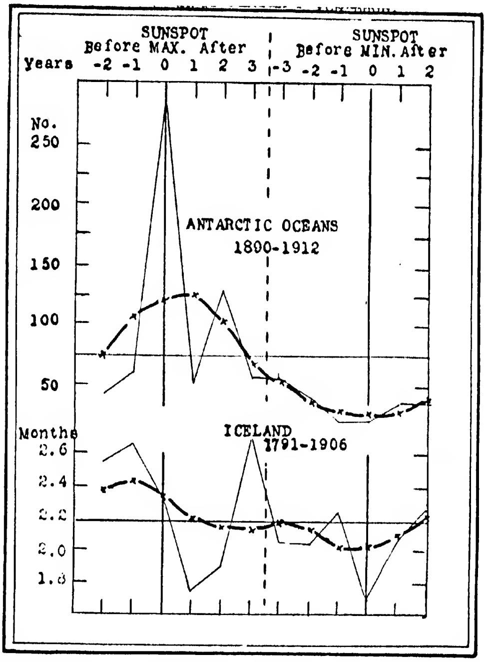
shows clearly a maximum snowfall near sunspot maximum and a minimum snowfall near sunspot minimum. This fact is in good agreement with the lower temperatures at sunspot maximum. By reference to Fig. 237 it will be seen that the trend of the snowfall curve is the opposite to that of the total annual precipitation at Blue Hill, mostly rainfall.

The relation of snowfall to sunspots is not so apparent at

Sierra, California, but the mean snowfall around sunspot maximum is distinctly higher than around sunspot minimum.

Fig. 242 shows the number of icebergs observed in the southern oceans as given in the *Memoirs of the Meteorological Office of India;* and also the duration of ice on the coast of Iceland.

FIG. 242



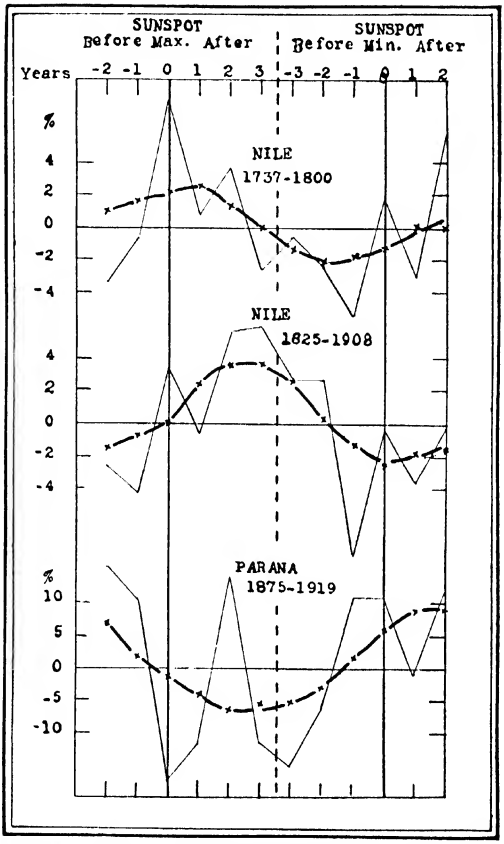
Number of Icebergs and Duration of Ice for Each Year of Sunspot Period

The period of observations of the icebergs only goes back as far as 1890, but the curve indicates a very close connection between the number of icebergs and sunspots. The result is probably determined by an increase in the atmospheric circulation indicated by the relation of atmospheric pressure to sunspots previously described.

The amounts of ice on the coast of Iceland were taken from the records gathered by Meinardus [10] and extend back to 1791. The

[10] Meinardus, W., *Ann. d. Hyd. und M. M.*, 1906, p. 148.

FIG. 243



Mean Heights of the Nile and Parana Rivers for Each Year of the Sunspot Period

relation to the sunspot is not close, but the smoothed curve shows that in general there is a greater quantity of ice about sunspot maximum than about sunspot minimum.

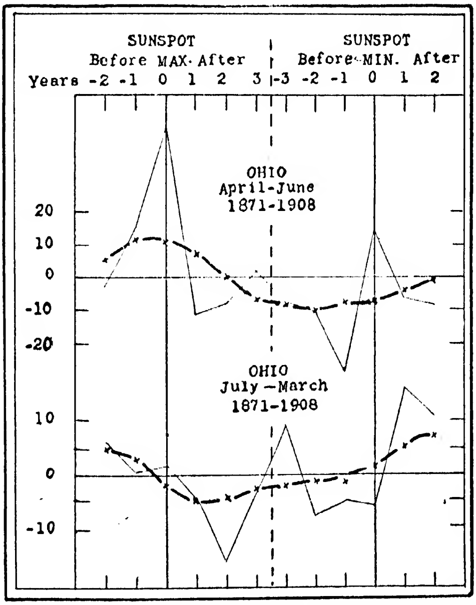
RIVER HEIGHTS AND SUNSPOTS

Fig. 243 gives the mean heights of the River Nile from observations during two centuries derived from figures published in the "Memoirs of the Meteorological Office of India." In both cen-

turies the water averaged higher at sunspot maximum than at sunspot minimum; but in the later epoch, there was a lag in the maximum height of the Nile in relation to the sunspot maximum.

The Nile rises in equatorial regions and its maximum height near the maximum of sunspots corresponds to the maximum of rainfall found in the equatorial belt and illustrated in Fig. 237.

Fig. 244



Mean Height of the Ohio at Cincinnati for Each Year of the Sunspot Period

The mean heights of the River Parana at Rosaria, Argentina, for each year of the sunspot period, are plotted in the lower part of Fig. 243. The course of the smoothed curve is opposite to that of the Nile and corresponds more nearly to the rainfall of middle latitudes shown in Fig. 237.

The relation of the mean height of the Ohio to sunspots is different for different seasons as shown by the plots (Fig. 244) of the mean heights derived from observations at Cincinnati. In spring and early summer, the river is higher with the greater number of sunspots; but for the remainder of the year it appears

to be lower. That the relation of the higher water in the spring month is due in part to the melting of snow which falls in greater amount near sunspot maximum seems evident from the fact that the departure from the normal height of the river during the winter months, before the melting of the snow, is opposite in sign to that in April and May.

STORM TRACKS AND SUNSPOTS

Kullmer's [11] researches show that there is an increase of frequency in cyclonic storms both in the north and in the south of the United States at sunspot maximum as compared with sunspot minimum, and a reverse condition in the central United States.

[11] Kullmer, C. J.—*Second Pan American Scientific Congress Proceedings*, Vol. II, pp. 338-393, Washington, 1917.

CHAPTER XIII

FORECASTING THE WEATHER

SUMMARY

The forecasting of the weather is treated from the standpoint of:

(1) Local forecast from local observations.
(2) General forecasts for one or two days in advance from weather maps and:
(3) Forecasts based on the relations of the weather to solar radiation.

A detailed explanation is given of the latter method of forecasting in Argentina.

ONE of the most thorough tests of knowledge and one of its most desirable aims is prediction, so that man may avoid, or at least to some extent counteract, the evils which beset him. Foreknowledge of the weather will not enable one to avoid all loss from changes of the weather nor escape all the discomfort and unhappiness which unfavorable weather conditions may cause, but it would render it possible to prevent a large part of the losses and a large part of the discomfort, the total of which is very great, as was pointed out in the *Introduction*.

All sorts of devices have been used in forecasting the weather, many of them of value, some of them of no value when subjected to careful tests.

FORECASTS FOR A FEW HOURS FROM LOCAL CONDITIONS

As the early knowledge of weather began with observations by individuals at isolated spots on the globe without reference to any other spot, so weather forecasting began with the information gained from such observations. It was based on the forms and the colors of the clouds, the direction of the wind, the effects of the humidity of the air on plants, the colors of the sky, the physical discomfort of man and beast. After instruments were invented the best local forecasting depended not only on observations of the sky but also on interpreting correctly the readings of the thermometer, the barometer, the wind-vane and

anemometer, the hygrometer, etc. Local forecasts based on this knowledge are still largely made by the community and to many people are more important than any other form of forecast.

Indeed for a few hours in advance it is perhaps the best basis for forecasting available to the public. When the wind is from the direction of the equator or from some easterly point, the air humid and the sky overhung with dark, low clouds, rain is imminent, in fact is likely to occur within from one to three hours. If the sky is covered with a gray sheet of alto-stratus, thickening toward the west, rain is not so imminent, but is to be expected within a few hours, usually six to eight with a probability of over 60 per cent, as determined from observations at Blue Hill, Mass. If there are high clouds of the cirro-cumulus or alto-cumulus type, rain is indicated with a less degree of certainty, at Blue Hill with a probability of 40 to 50 per cent within 16 hours or so. Following the appearance of cirrus the probability of rain within 24 hours is not much greater than the average probability of rain under all conditions. The directions from which the higher clouds move also materially influence the probability of rain. When these clouds have a component of motion from an equatorial direction, the probability of rain increases and there is likely to be a fall of temperature, especially if the movement of the cloud is rapid. Cirrus with a component of motion from the pole indicates rising temperature which is likely to be followed later by falling temperature and rain. Cirrus is sometimes observed with a component of motion from the equator after the occurrence of rain, but always indicates colder weather to the west or northwest of the observer, so that after the rainfall has ceased fine, cool weather is to be expected for two or three days.

The physical discomfort of man and animals, more especially in summer, has long been associated with the probability of rain. This discomfort is to a large extent brought about by a combination of high temperature and high humidity, perhaps aided by the peculiar electrical conditions and by falling pressure. High humidity with the temperature near the freezing point and a brisk wind is also a cause of discomfort in winter which usually precedes snow.

The effect of high humidity on plants, producing the cupping of leaves or other changes of appearance in the plant, is also frequently used for making forecasts of rain.

Optical appearances such as halos in the advancing edge of a sheet of cirro-stratus or coronas within a sheet of alto-cumulus, especially if the wind is from an equatorial direction and the

temperature is rising, are additional evidence of the probability of rain within 24 hours.

Sky colors also have been immemorially an aid to short-range weather forecasting. From the earliest historic times there are quotations showing that sunset and sunrise colors have formed a basis for weather forecasts for the same day or the succeeding day. In English these signs have embodied themselves in such rhymes as

"Evening gray and morning red,
'Twill pour down rain on traveler's head;
But evening red and morning gray
Will set a traveler on his way."

All such forecasts are based on the fact that storms move in general from west to east, and dense banks of condensed vapor towards the west cut off the colors and light of the sun, so that when it sets in a gray mass the approach of conditions favorable for rain is indicated. On the other hand, when the gray is found in the east at sunrise, the storm has already past or is passing. A rosy sunset indicates fair weather toward the west, from which direction the weather to be expected comes. The normal sequence in sunset and sunrise colors will be understood from reading Chapter IX.

Unusual transparency of the air and pure twilight colors indicate cooler, fair weather for the next day, although frequently followed within two days by additional rain; while hazy air, in which the sun sets as a fiery ball, attends droughty conditions with temperature above the normal of the season.

When meteorological instruments are available a rapid decrease in pressure or a rapid rise in temperature is an indication of rainfall and wind within a few hours, followed by cooler fine weather.

The spectroscope is sometimes used to estimate the amount of moisture in the atmosphere by the darkening of the vapor bands and is of considerable use for short range forecasting.

But with every available source of information obtainable at the earth's surface there must be at times uncertainty of coming conditions for lack of information of conditions in the upper air. Were plots of conditions in the free air like Fig. 164 easily obtainable local forecasts could be made with much greater probability of success.

Weather forecasts for coming seasons from the behavior of

animals or the conditions of plants have not been shown to have any scientific basis or any value.

FORECASTS FROM WEATHER MAPS

As soon as observers at isolated stations began to compare their observations, it was discovered that similar weather conditions existed over wide areas and that there were systematic wind circulations and progressive movements of the whole system. H. W. Brandes[1] in Europe was the earliest to collect and publish charts or maps showing the distribution of weather conditions. His work was followed by similar investigations by Leverrier in France, by Fitzroy in Great Britain and by Espy and Loomis in the United States. The invention of the telegraph made it evident that one of the uses to which it could be applied would be the rapid collection of weather information from a large area, charting it and using it as a basis for a new method of weather forecasting for the benefit of commerce and agriculture. A government weather service for such a purpose was begun in Great Britain in 1854, and in France in 1855 although the practical application did not begin until 1863. In other countries they began at successively later dates until now the whole world has such services.

Twice a day at certain fixed hours the observers in each country begin the work of observing the weather at the same moment. When the observations are finished they are translated into a cipher message and transmitted to a central office where they are deciphered and charted on maps which then give a bird's-eye view of the weather over the whole country only a short time before.

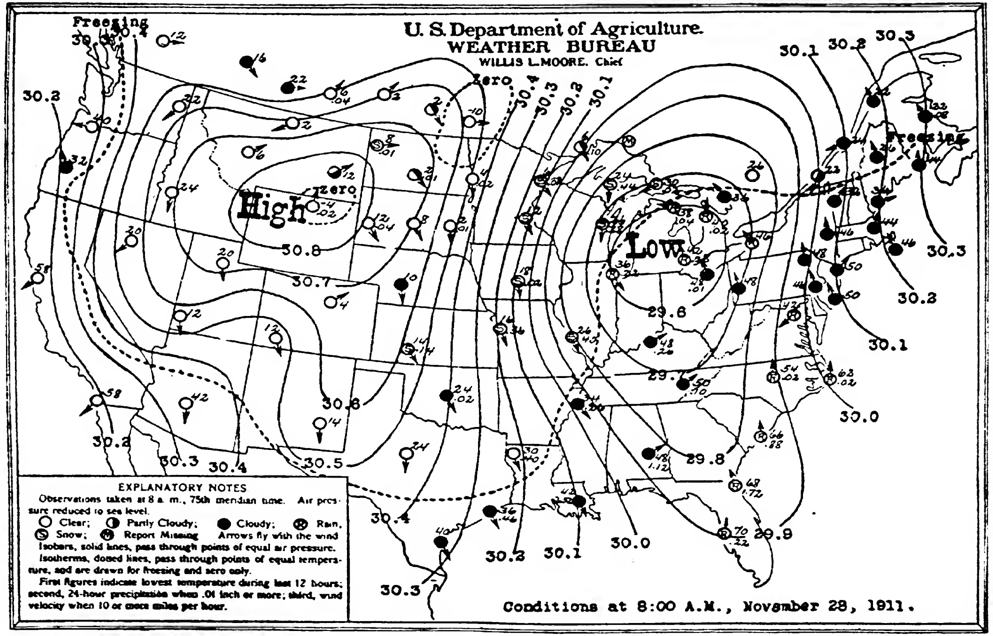
The observations reported are of pressure, temperature, wind direction and velocity, rain and snow, humidity, fog, clouds (classified into different types), cloud movements, thunderstorms, frosts, hail, smoke, haze and optical phenomena such as auroras, halos, coronas, etc.

A copy of a weather map such as is published at certain important stations in the United States is given in Fig. 245.[2] The locations of the observing stations are indicated by circles. Where cloudiness prevails the whole area of the circle is blackened; for partly cloudy one half of the circle is blackened; while the whole circle is left clear to represent clear skies. If rain

[1] "Beiträge zur Witterungskunde," Leipzig, 1820. "Dissertates physica, etc.," Leipzig, 1826.

[2] Bliss, George S.—"Forecasting the Weather," p. 12, Washington, 1913.

FIG. 245



United States Weather Map—After G. S. Bliss

is falling at the time of observation an "R" is substituted for the circle, or an "S" for snow. The arrows fly with the wind, that is, an arrow head pointing toward the south means a wind from the north.

The temperature and the depth of precipitation (rain or melted snow) are written by the side of each station in the figures. The continuous lines on the chart are lines of equal pressure drawn for each tenth of an inch. The "Low" shows the region where the pressure is the lowest and the "High" the region where the pressure is the highest. The dotted line marked "Freezing" connects those stations where the temperature is 32° F. (0° C.) and the dotted line marked "Zero" shows the region where the temperature is zero Fahrenheit.

In the central station where forecasts for the entire country are made the general weather map is supplemented by a number of additional maps. In general these show: (1) the changes of pressure during the past three, twelve or twenty-four hours; (2) the temperature changes during the past twenty-four hours; (3) the highest and lowest temperature at each station during the past twenty-four hours; (4) the departure of the temperature from the normal for the given hour and time of year; (5) the amount of precipitation on which are drawn lines of equal precipitation during the past twenty-four hours; (6) the amounts and kinds of clouds and their directions of motion. In some cases charts are also constructed showing the distribution of humidity. In Sweden charts showing lines of equal air density were initiated by Ekholm and in Norway charts have been introduced by Bjerknes showing detailed observations of wind movement as illustrated in Chapter VI.

Probably the most important of these supplementary maps for the forecaster are the maps showing the three, twelve and twenty-four hour changes of atmospheric pressure. These changes serve to analyze the changes to some extent into rapid moving or slow moving waves and to show the direction of motion of the system.

Large three-hour changes and smaller twenty-four hour changes indicate rapid moving atmospheric waves; while small, irregular three-hour changes and larger twenty-four-hour changes indicate slower moving waves. Changes due to progressive movement are, however, mixed with those arising from changing intensity of the areas of high and low pressure. The changes of intensity without drift are estimated by comparing the current weather map with the preceding one. Changes in intensity at

the place of highest and lowest pressure can thus be noted, and also any increase or decrease in the temperature gradient or any changes in the direction or velocity of the winds and clouds, all of which are factors in determining changes in the intensity of the areas of high and low pressure. Guilbert worked out some elaborate rules for estimating the changes of intensity of barometric depression from certain distribution of winds, and was reasonably successful in their application, but so far his methods have not come into general use.

Drawing a line between the winds with equatorial and polar components of motion and noting its relation to the rain areas and its progressive motion has long been in use by forecasters, but the work of Bjerknes has greatly accentuated its importance.

In the Argentine Weather Service the experiment has been tried of expressing numerically and graphically on maps the distribution of pressure to be expected twelve or twenty-four hours later. The process depends on the progressive movements of the barometric changes which are projected ahead for twelve or twenty-four hours and added to the observed distribution of pressure to-day to obtain that of to-morrow.

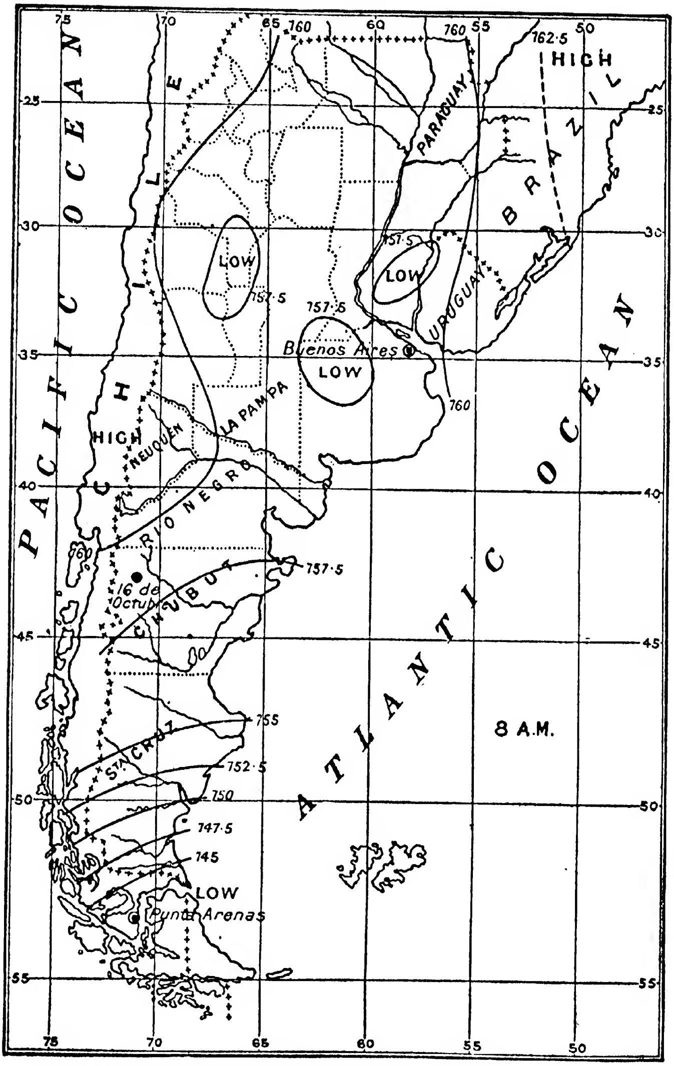
The estimate of the progressive movement of the areas of barometric change may be made from experience of similar conditions or from the actual movement of the changes during the preceding or the past twenty-four hours. When the changes progress toward the equator a diminution for diminished latitude must also be allowed for. In Argentina a decrease of about 20 per cent for a change of 10° of latitude was a rough approximation.

These changes of pressure shifted in position are then added to the observed pressures in order to get the predicted pressures for the next day and from these predicted pressures the anticipated distribution of pressure is mapped out. From the predicted distribution of pressure the winds, the temperature and the weather to be expected the next day may be anticipated with the aid of the changes of temperature observed during the past twenty-four hours.

In practice the process can best be accomplished by means of a transparent piece of paper on which a map is printed. This map is displaced by an amount equal to the expected movement of the area of pressure change, but in the opposite direction, and then laid over the pressure changes of to-day, which with such modifications as are necessary may be considered the changes to be expected in the new position to-morrow.

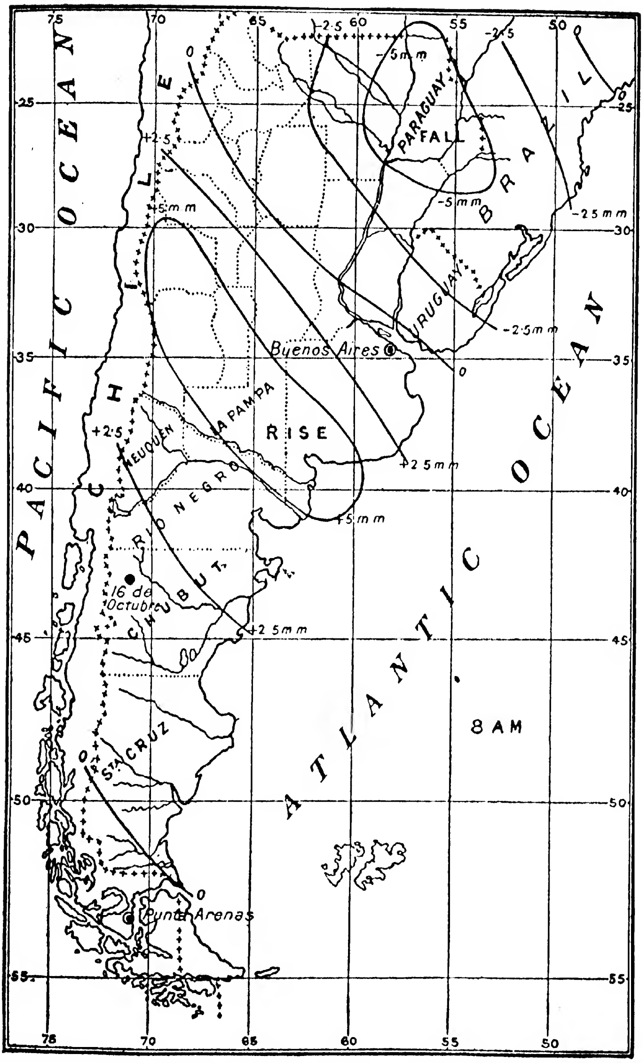
The process is illustrated from the following charts obtained

Fig. 246



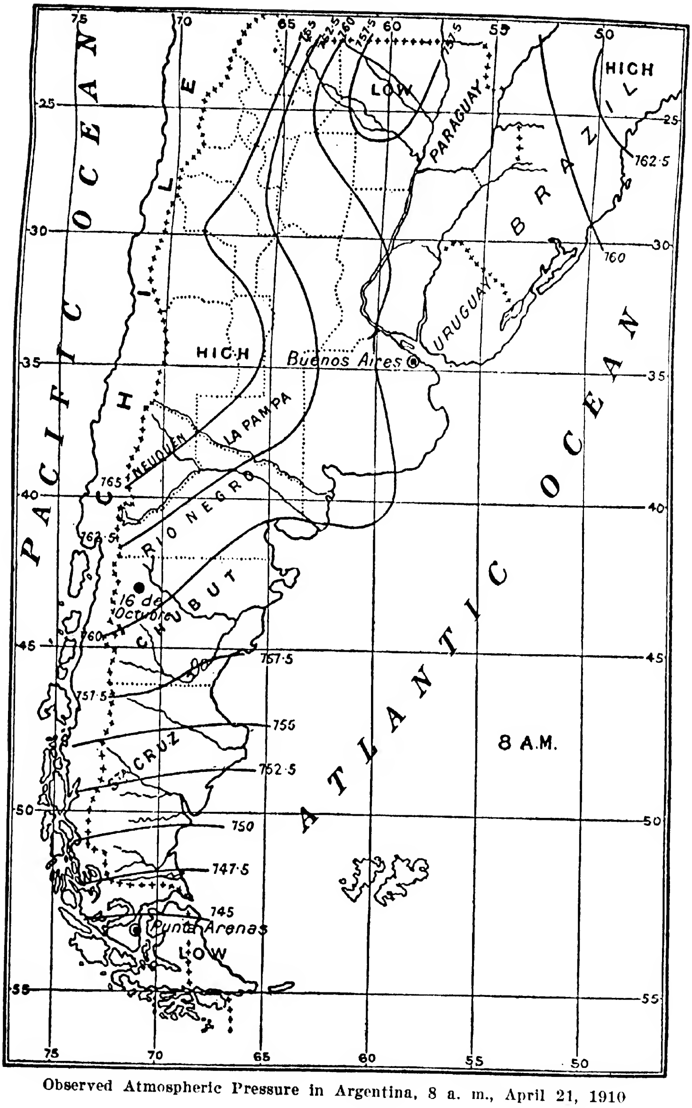
Atmospheric Pressure in Argentina, 8 a. m., April 20, 1910

FIG. 247



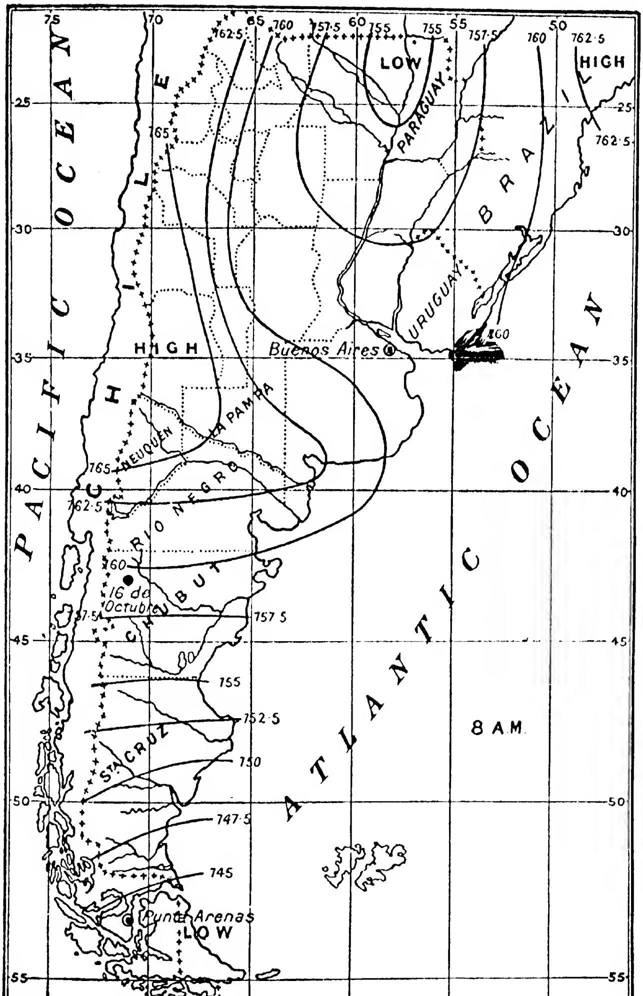
Predicted Change of Pressure between April 20 and April 21, 1910, in Argentina

FIG. 248



Observed Atmospheric Pressure in Argentina, 8 a. m., April 21, 1910

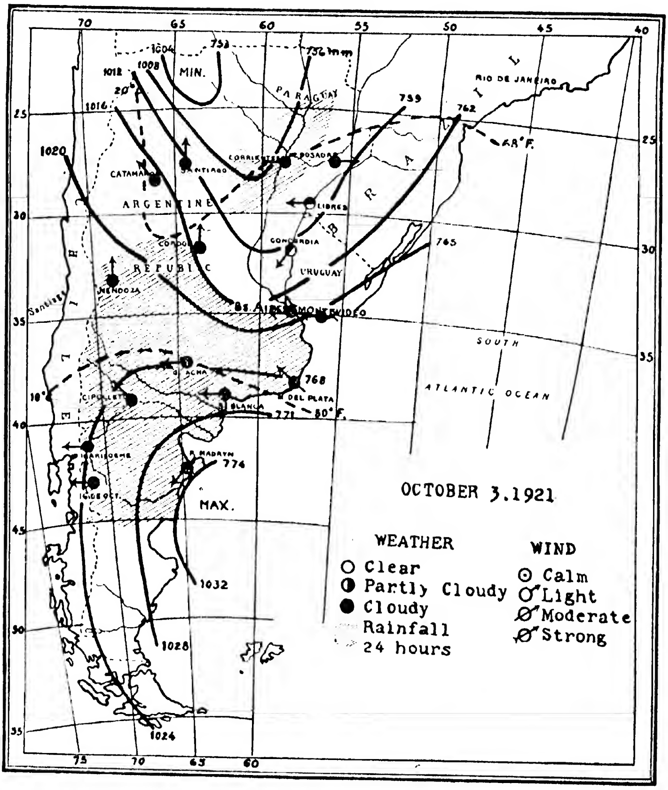
FIG. 249



Predicted Atmospheric Pressure in Argentina, 8 a. m., April 21, 1910

in actual practice. Fig. 246 [3] shows the observed pressure distribution found in Argentina on the morning of April 20, 1910, Fig. 247 illustrates the predicted changes of pressure for the succeeding twenty-four hours. Adding these changes to the ob-

Fig. 250



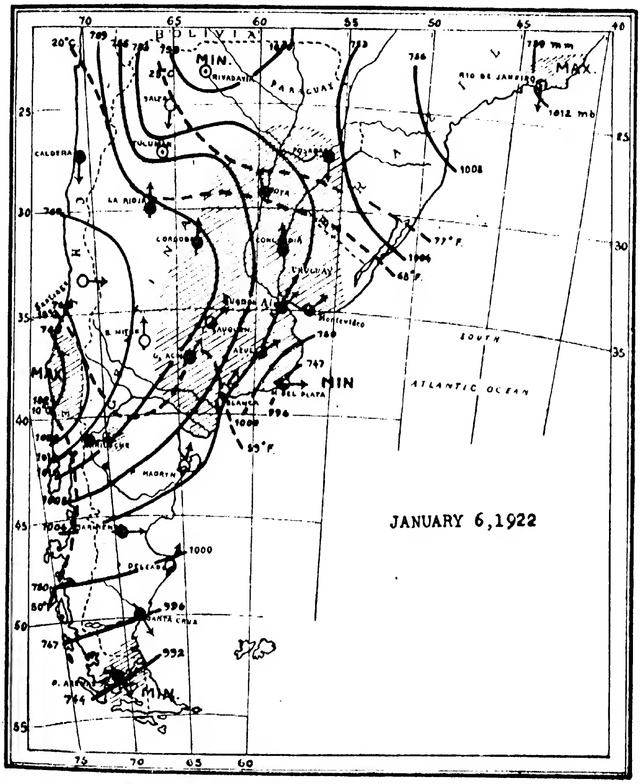
Argentina Weather Map for 8 a. m., Oct. 3, 1921—Rain Type

served pressures a map of the distribution of pressure to be expected on the morning of April 21 was constructed and is shown in Fig. 248. In Fig. 249 is seen the observed distribution of pressure as obtained from the telegraphic reports on the morning of April 21.

[3] From *Quar. Jour. of Roy. Met. Soc.*, Vol. 41, p. 202, London, July, 1915.

The amount of rainfall to be expected from any given distribution of pressure is determined from the wind system called for by that distribution and by the prevailing humidity. When the humidity is high and the winds are drawn from the ocean

FIG. 251



Argentina Weather Map for 8 a. m., Jan. 6, 1922

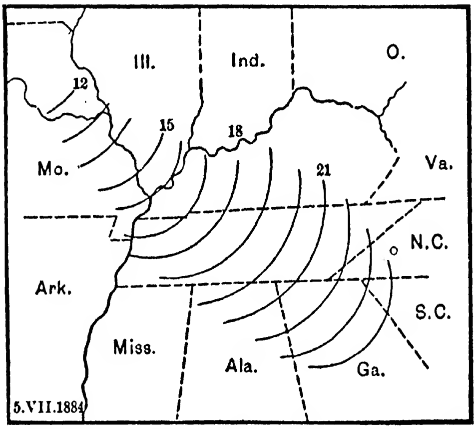
and converge toward an area of low pressure the rainfall is likely to be large. The precipitation is accentuated where the winds rise over hills and mountains and where winds with an equatorial component of motion encounter and overrun polar winds.

Fig. 250 shows the distribution of pressure, winds and temperature which accompanies heavy rainfall in Central Argentina

while Fig. 245 shows the type of isobars, which usually bring general rains in the eastern United States. On the same map, Fig. 245, fair weather conditions are shown in the western half of the United States. Under normal conditions this area of high pressure and fine weather would drift over the Eastern States within two days.

Closely crowded isobars like those shown in Fig. 251 are productive of high winds and show the distribution of pressure producing a *pampero* in the region of the La Plata River.

FIG. 252

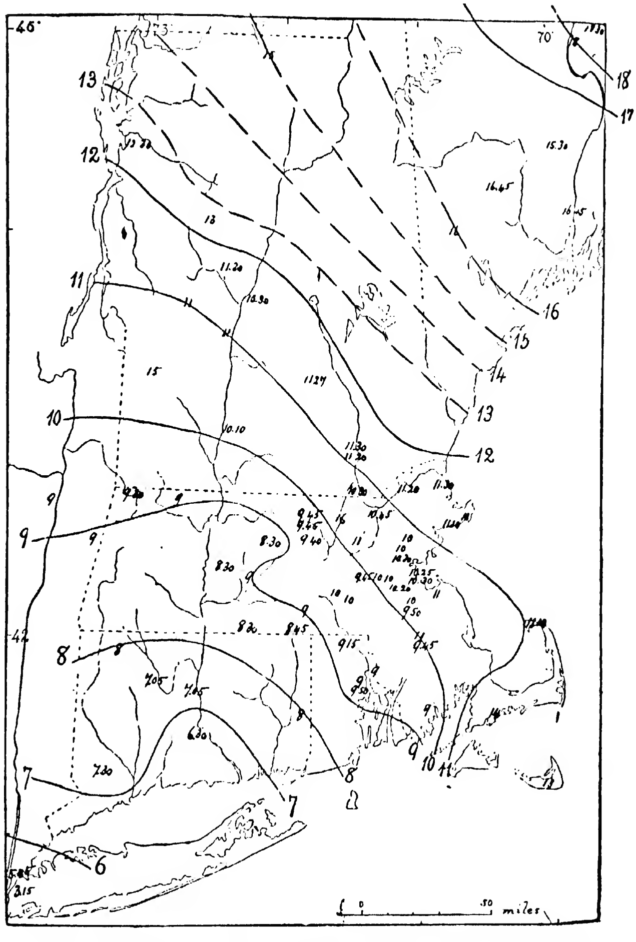


Thunder squall in Central United States

Rainfall and cloudiness are nearly always found in regions where the isothermal lines are crowded closely together as illustrated in Fig. 145 and is to be looked for under such conditions within the areas of the steep gradients of temperature except in arid regions.

It would be possible to make even more detailed forecasts of the weather than are made at present if the network of telegraphic stations were close and the rain-front was followed from point to point as it developed. It is well known that line squalls and thunderstorms frequently extend over great distances and progress with fairly uniform velocity for many hours at a time. Fig. 252 shows a thunder squall which developed in central Missouri and traveling southeastward reached northern Alabama

FIG. 253



Time of Beginning of Rain, October 13, 1885—After Winslow Upton

during the following night. Had it been followed by telegraph its arrival at various points along its path might have been anticipated for several hours. Many years ago Professor F. E. Nipher, of Washington University, suggested telephoning ahead the formations of thunderstorms for the use of farmers.

Professor W. Upton[4] has shown that in New England the rain-front progresses frequently with great regularity and the beginning of rain at points in advance might be told to the hour for a short time in advance. (See Fig. 253.)

Richardson has recently shown that the weather conditions shown on a weather map may be subjected to very rigid mathematical calculation, so that, in time, future conditions for a few hours in advance may be calculated with great accuracy and refinement.

Atmospheric changes are so rapid, however, that forecasting from weather maps cannot extend beyond a distance of one or two days in advance, and even then with rapidly diminishing accuracy.

FORECASTS BASED ON THE RELATIONS OF THE WEATHER TO SOLAR CHANGES

Realizing the limits of forecasts made from the weather map both in time and in accuracy many efforts have been made to find a better method of forecasting. As solar heat is the accepted cause of weather changes, it was natural to seek in solar changes a method of forecasting the future. The weather services of India and of Argentina have taken the greatest interest in these developments. In India such forecasts are chiefly for seasons and are based on the studies of Blandford, Elliot, Walker and Lockyer in regard to the relation between the sunspot period of about eleven years and the weather. In Argentina the forecasts are usually for a shorter interval about eight days in advance and are based on the studies outlined in previous chapters dealing with the relation of the weather to the changes of solar radiation from day to day. In making the forecasts use is made of the measurements of the Astrophysical Observatory near Calama, Chile, supplemented by the observations of faculæ made at La Plata and at Pilar, all of which are telegraphed to the central office of the Argentine Weather Service. The forecast department has been able to devote a great deal of time to the development of these methods, owing to the progressive spirit of George O. Wiggin, the present director.

After a preliminary study by the writer of the relation of the changes in solar radiation to the weather of the world, the results of which were published in the *Smithsonian Miscellaneous*

[4] *American Meteorological Journal,* Vol. 3, p. 318, Detroit, November, 1886.

Collection, Vol. 68, No. 3, it was thought that the measurements of solar radiation would be of use in extending the period now usually covered by weather forecasts in Argentina. Accordingly an arrangement was made with the Smithsonian Institution to transmit the observations made in Calama, Chile, to Buenos Aires by cable, the All-American Cables Company kindly consented to coöperate in the work. From all the available observations made previously by the Astrophysical Observatory at Mount Wilson, California, normal curves of temperature were prepared for thirty days following solar radiation values of different intensities. A part of these data was published in the *Smithsonian Miscellaneous Collection*, Vol. 71, No. 3. With these cabled reports and the normal temperature curves following different radiation values as a guide the measurements of solar radiation were made the basis for weekly forecasts for the region of the River Plata in Argentina beginning with December 12, 1918.

In the meantime systematic investigations were carried on to discover the influence of solar radiation on the weather not only of Argentina but of all parts of the world. The results of these investigations seem to fully establish the following rules:

1. That whenever there is an increase of solar radiation, either of long or short period, there is a fall of pressure in the equatorial belt of the earth and a rise in certain favored regions in higher latitudes, which may be called centers of action.
2. From these favored regions waves of pressure move outward, which form the traveling waves of high and low pressure of temperate zones. These waves vary in intensity with the solar radiation and are clearly produced by them.
3. There is a distinct annual and semiannual period in the solar influence. The equatorial belt of greatest depression of pressure with increased solar radiation moves north and south with the sun, and the centers of action in temperate latitudes shift their positions radically; so that the influence of the solar radiation at any place may be direct at one time of the year and inverted at another. For this reason it is necessary to work out for each region normal curves for each month separately.
4. Different intensities of radiation act differently, so that for each month it is necessary to work out a normal

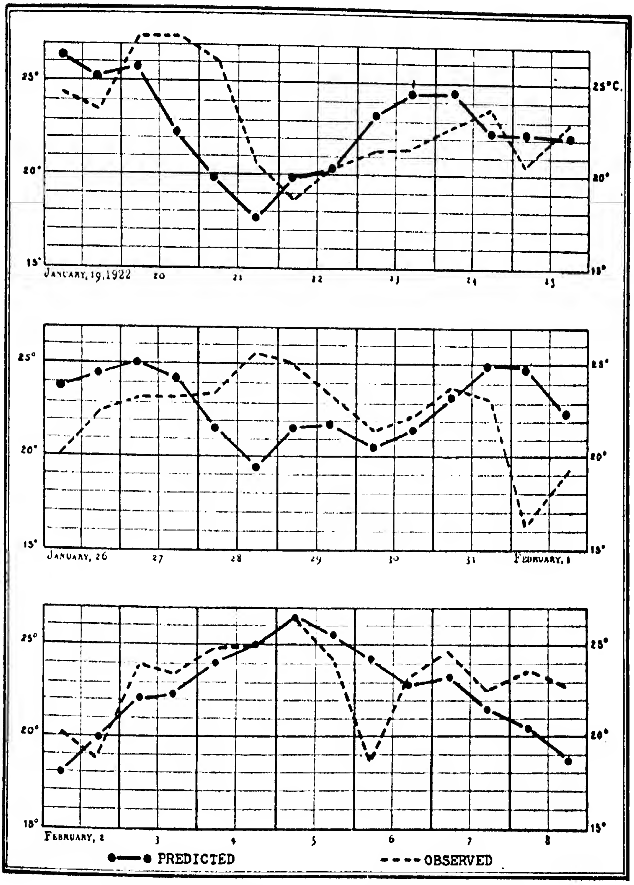
curve for each region of the earth for each intensity of solar radiation. The observations of solar radiation are not numerous enough, nor exact enough, to enable this to be done with accuracy; but an approximation has been obtained for the region around Buenos Aires.

Besides these difficulties of interpretation the forecaster has only one station from which reports of solar radiation are obtained. Owing to unfavorable conditions, these measurements are frequently interrupted for days and sometimes for weeks. It hence became evident that, if regular forecasting was to be done, some method must be found of estimating changes of solar radiation to complement the measurements with the bolometer. Dr. Abbot has found that there is a relation between the annual amount of spottedness on the sun and the mean solar radiation intensities, and it seemed possible that visual observations of the sun might furnish an indication of day-to-day changes in solar radiation. In August, 1920, an arrangement was made with the Astronomical Observatory of the University of La Plata to coöperate with the Argentine Weather Service in taking observations of visible phenomena on the surface of the sun. Accordingly, observations were begun at La Plata by Mr. B. Dawson and his assistants, and recently these have been supplemented by observations at the Magnetic Observatory of the Argentine Weather Service at Pilar, so that now nearly a complete record of the solar surface is obtained. With the additional aid of the National Observatory of Brazil at Rio Janeiro, the record is nearly complete.

A preliminary study of the relation of the spots and faculæ to solar radiation was published in *Nature*, Vol. 106, p. 630, and Vol. 107, p. 108 (see Fig. 224), and later observations seem to confirm fully the views there presented. The radiation values appear to have a close relation with the faculæ. An increase of brightness caused by the faculæ in certain regions of the sun is correlated with an increase in the total radiant energy coming from the sun, that is an increase of light is correlated with an increase of heat. Since the faculæ are most visible on the edge of the sun where there is great absorption and the background is relatively dark, it follows that an outbreak of faculæ near the edge of the sun is equivalent to an increase in the total effective radiating surface of the sun. The observations at La Plata indicate that the greatest effect is when the faculæ are at a distance of 70–80 degrees from the central meridian of the

sun. It follows from this fact that when a cloud of faculæ have produced their greatest effect on the east limb of the sun they reappear eleven days later with a maximum effect on the west

Fig. 254

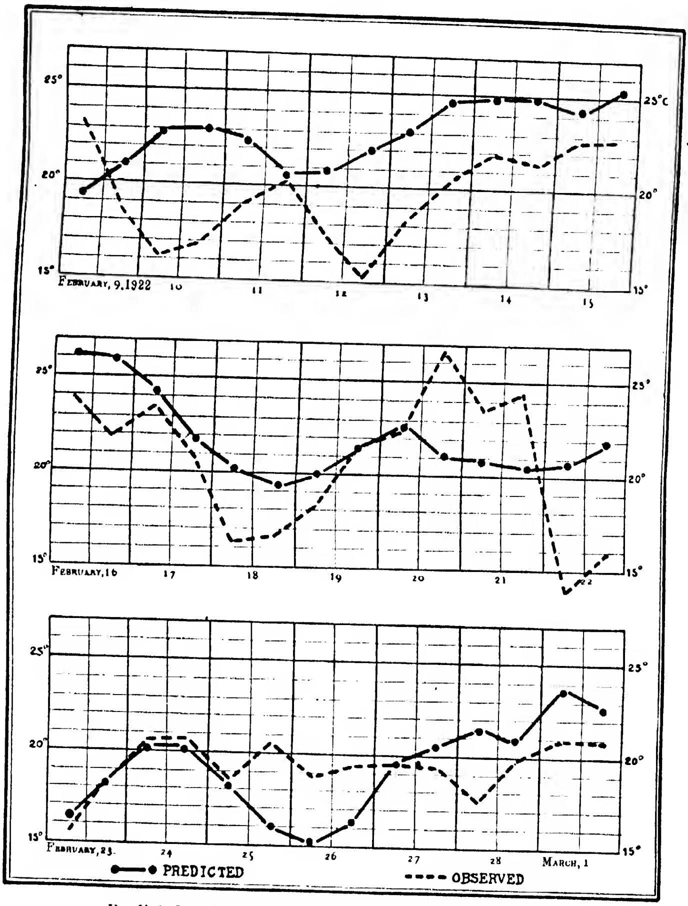


Predicted and Observed Temperature in Buenos Aires

limb, having moved in the meantime 150° (75x2) by the sun's rotation. Also, if they are very bright on the west limb of the sun they are likely to reappear 16 to 18 days later on the east

limb. This correlation suggested a rational explanation of the tendency of high radiation values and of terrestrial temperatures to repeat themselves at intervals of 11 or 17 days, which is shown

FIG. 255



Predicted and Observed Temperature in Buenos Aires

by the curves in the Smithsonian publication, *Miscellaneous Collection*, Vol. 71, No. 3 (see Fig. 223, also Fig. 228). At times it is also possible to utilize the full solar rotation of 27 days, but

in many or most cases the increased radiation dies out before the completing of the interval. It is thus found that the two classes of solar observation strongly supplement each other, and suggest repetitions which are interwoven into the new system of forecasting now being developed in Argentina.

From the very first, it was believed that quantitative predictions were desirable in order to measure progress, and consequently exact forecasts of the temperature to be expected in Buenos Aires at 8 h. and 20 h. of each day are made for a week and issued the day before the beginning of the week. These are based, first on the annual and diurnal normal obtained from 30 years' observations in Buenos Aires, and second on the deviations from the normal anticipated from changes in solar radiation.

These forecasts are expressed in the form of curves, samples of which for the six weeks beginning January 19, 1922, are reproduced in Figs. 254 and 255. The curves for each week give the predicted temperatures in full lines and the observed temperatures in dotted lines for the six weeks. These are the last available reports. As is to be expected there are occasional failures in the forecast, but eliminating the annual and diurnal periods there has been an increasing positive correlation between the abnormal temperatures and the predicted temperatures.

The correlation between the observed and predicted temperature is not high, but the belief seems justified that, whenever full and accurate day-to-day values of solar radiation are available, weather forecasting for all parts of the world may be made with an accuracy and for intervals in advance not heretofore thought possible by scientific men. Forecasts of coming seasons will be possible as soon as the repetition of solar variations in sunspot periods and other long period changes can be anticipated with reasonable accuracy.

CHAPTER XIV

THE METEOROLOGY OF THE SUN

SUMMARY

A description is given of conditions observed on the sun and of the methods of studying and interpreting solar conditions. Sunspots are shown to be great cyclones in the surface of the sun in comparison with which the most terrific terrestrial cyclones sink into utter significance.

The faculæ are found to be intensely hot gases sinking back into the interior of the sun. They are probably gases previously ejected from the interior of the sun and as they sink back become intensely hot.

The prominences are described as gases shot outward with immense velocity from the interior of the sun to immense heights in the solar atmosphere, and are cooled by expansion so that when seen against the bright solar surface in photographs made by the spectroheliograph, they appear dark.

The general circulation of the solar atmosphere is considered and such observations described as have tended to disprove or establish it.

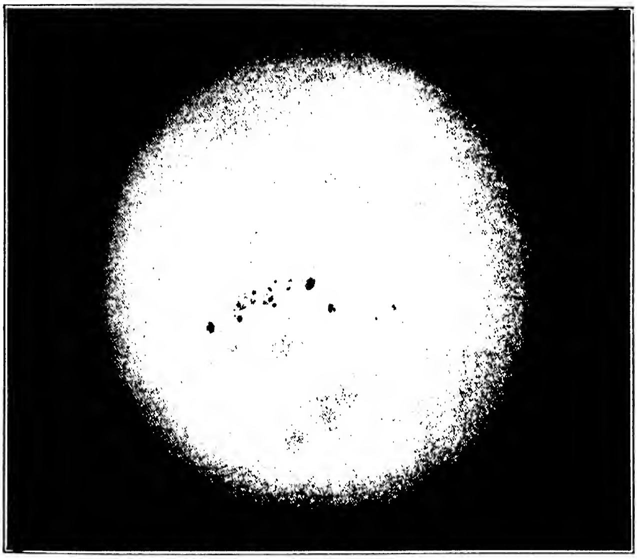
CONDITIONS OBSERVED ON THE SUN

THE fiery tempests which toss and heave on the surface of the sun are on a scale of magnificence which almost defies human imagination. In their midst the entire earth might be swept about, as the tempests frequently cover an area many times greater than that of the earth.

If terrestrial tempests are but feeble reflections of these tremendous outbursts of solar energy, then the history and causes of these solar tempests become of the greatest interest to the student of terrestrial weather.

To the human eye the sun appears as a whitish disk, so brilliant that it cannot be viewed without pain. Only at the rare intervals of total eclipses, when its surface is hidden by the dark disk of the moon, does the human eye get a glimpse of the vast forces at play within and around the solar surface. Around the surface on such occasions are seen vast jets of reddish light, whose heights are estimated at hundreds of thousands of miles. These jets have received the name of *prominences*, and the encircling ring of light out of which they rise is called the *cromosphere.* By means of the *spectroheliograph* these can now be

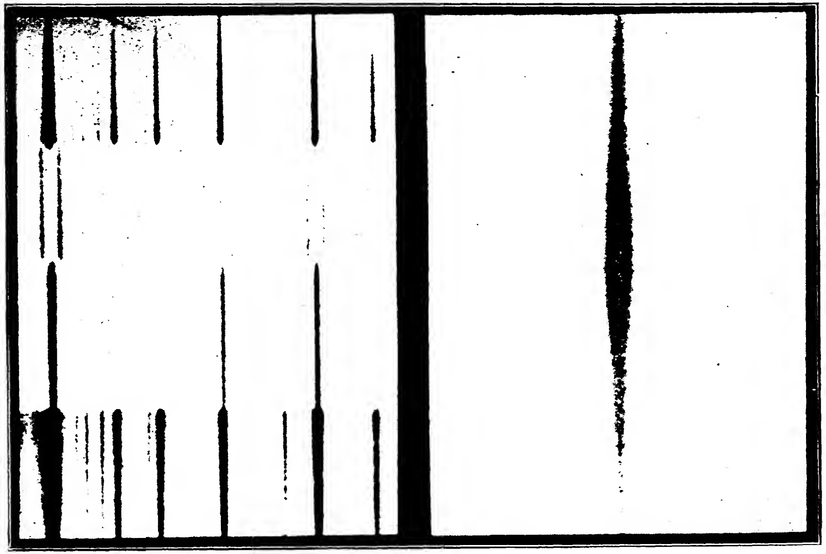
PLATE XI



The Sun, March 20, 1920. Mount Wilson Solar Observatory; Showing Group of Large Spots

From the "Annals of the Astrophysical Observatory of the Smithsonian Institution," Part IV

PLATE XII



a b

(a) Doubling of Lines in the Magnetic Field.
(b) Doubling of Lines in the Umbra of a Sunspot—After E. C. St. John.

N

E

W

Photo. by Yerkes Observatory

S

Spectroheliogram of the Sun, August, 1903, Showing the Spots, Cloccull, and General Appearance of the Bright Surface of the Photosphere—From *Monthly Weather Review*, July, 1905

PLATE XIV

Photo. by Ellerman

Prominence Beyond the Edge of the Sun

PLATE XV

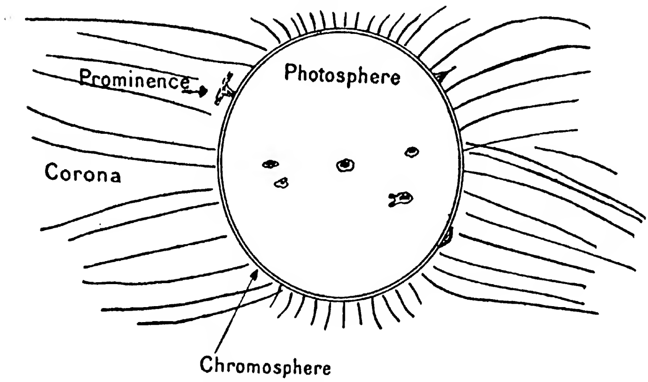
Photo. by Ellerman

Prominence Projected on the Sun's Disk

photographed in full sunlight. Surrounding these and extending outward from the sun to a great distance is a pearly white substance of filmy structure called the *corona.*

If under ordinary conditions, the sun is viewed through a telescope and its brilliancy diminished by being seen through a darkened glass, or by other means, it is found that its bright surface, or *photosphere,* has a granulated or willowleaf appearance; while here and there are seen more brilliant areas called faculæ and other darker areas which have received the name

FIG. 256



Solar Phenomena—After Duffield

of sunspots. These spots have a central dark area called the umbra and a surrounding area less dark called the penumbra. Sometimes these areas are circular or elliptical in form, and at other times very irregular.

An outline sketch of these different conditions is shown in Fig. 256.[1] The faculæ which usually appear as bright areas between or surrounding the spots are not shown In this figure the axis of the sun is vertical with the south poles above and the north below, because the sun is seen inverted in a telescope. The spots stretch across the equatorial zone and the rotation of the sun is from left to right. A spot takes about 13½ days to pass by rotation from one edge of the sun to the other.

The spots and faculæ are undergoing continual changes and can rarely be followed through more than one or two rotations,

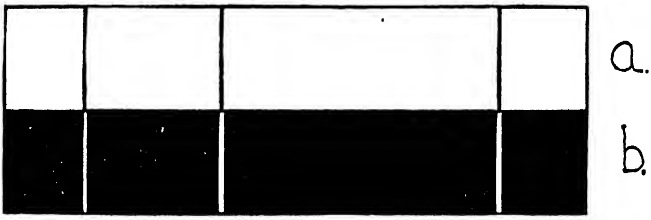
[1] From *Quarterly Jour. of Royal Meteor. Soc.,* Vol. 41, p. 178, July, 1915.

although in exceptional cases they are observed through six more.

METHODS OF STUDYING SOLAR CONDITIONS

Our knowledge of the sun depends almost entirely on the radiant energy which comes from it in the form of light and heat. In the interpretation of the various conditions disclosed by this stream of radiant energy all of the knowledge of modern physics has been brought into play, especially at the Observatory of Mount Wilson in California and at the Kodaikanal Observatory in India. One of the most fruitful lines of research has been by means of the *spectroscope*. When a solid body heated

FIG. 257



Spectrum of Hydrogen Showing Absorption and Omission Bands—After Duffield

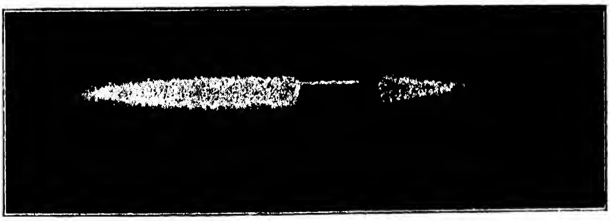
to a white heat has its light passed through a prism and projected onto a screen, the light is separated into different colors in a continuous gradation running from violet at one end to red at the other. If some substance sensitive to heat rays is passed along this "spectrum" it is heated. The indications of heat do not cease with the red of the spectrum but continue far below the red, thus disclosing invisible rays below the red, as outlined in Fig. 184. The separation of light is due to the fact that white light is composed of rays which have different rates of vibration. When the pulses or waves are close together, as in violet light, they are much more bent out of a straight line in passing through a prism than when the crests are farther apart, as in red light or in the dark region beyond the red.

When the light of an incandescent gas is viewed through a prism, it does not give a continuous spectrum as in the case of a glowing solid, but its light is found to be composed of bright lines which are different for each substance unless the gas is under very great pressure, 100 atmospheres or more, when cer-

tain gases become viscous and give a continuous spectrum. If the white light from a heated body is passed through an incandescent gas, the continuous spectrum is crossed by dark lines, and these dark lines are found to occupy the same place as the bright lines which are emitted by the incandescent gas. The lines of emission now become lines of absorption. The dark lines of absorption and the bright lines of emission in the spectrum of hydrogen are illustrated by *a* and *b* in Fig. 257.

The spectrum of the sun is found to have the character of a continuous spectrum crossed by dark lines, and hence the light comes from glowing white matter at a certain depth in the photosphere intercepted by incandescent gases in the outer atmosphere of the sun. Identification of the different gases in the solar atmosphere is found by comparing the bright lines emitted by incandescent gases in the laboratory with the dark lines found in the solar spectrum.

Fig. 258



The Broadening and Displacement of a Spectrum Line Produced Under Pressure—After Hale

Furthermore, it was found that when the incandescent vapor is put under great pressure the lines are broadened as illustrated in Fig. 258, where the narrow line represents a line in the spectrum of an incandescent gas at atmospheric pressure compared with the same line when the gas is at a pressure of 50 atmospheres.

The character of the lines is also related to the temperature of the gas as was determined by laboratory experiments. At low temperatures a certain arrangement of lines appears and as the temperature rises some of these lines disappear and others become visible, and at very high temperatures "enhanced lines" appear, so that the class or kind of lines in the spectrum enables the observer to determine the temperature of the substance from

which the light comes. Again, the lines found in light coming from an incandescent gas are changed when they come under the influence of a magnet. Certain of them are doubled and tripled in a peculiar manner which is called the Zeeman effect because discovered by Zeeman, (see Plate XII).

Studying the lines in the solar spectrum in connection with laboratory experiments on light, George E. Hale and his associates at Mount Wilson have made a very great advance in the knowledge of events happening at different depths in the solar atmosphere. By means of an ingenious arrangement, Dr. Hale was enabled to take photographs of the sun in different parts of the spectrum, that is, in monochromatic light. Thus it was found possible to take a photograph of the sun in the light coming wholly from hydrogen vapor and others from light coming wholly from calcium vapor. Even in the same band of light he obtained photographs at different levels in the sun's atmosphere by taking a photograph from each edge of the broadened bands such as those shown in Fig. 258.

Plate XIII shows a spectroheliograph of the sun taken at the Yerkes Observatory August 12, 1908, showing the spots, flocculi and general appearance of the bright surface of the photosphere.

Sunspots.—By means of these various studies, it has been possible to show: (1) that sunspots are great vortices in the solar atmosphere, sometimes revolving in one direction and sometimes in the other; (2) that the gases in the interior of the spots are cooler than those at other parts of the solar envelope; (3) that the hydrogen vapors at a high level in the solar atmosphere are drawn into the sunpots in spiral whirls, the direction of the whirl depending on the hemisphere in which it is found; sometimes, however, there are bipolar spots in which the whirl in one part is opposed to that in the other, and it is now suspected that all sunspots are bi-polar; (4) that the sunspots begin in the photosphere below the visible surface and can be detected by magnetic effects before they are visible.

"To account for the low temperatures of sunspots by expansion of the ascending gases in the vortex Mr. Russell finds that it is necessary to assume that the latter come from a depth at which the temperature is at least 10,000° C. It is probable that the temperature at the bottom of the ascending part of the vortex is at least 20,000° C., and that the expansion on rising to the surface is more than forty-fold." [2]

[2] Annual Report of the Director of the Mount Wilson Observatory, 1921.

Another method of studying the solar atmosphere is by the light displacements of the spectrum lines produced by movement of the solar gases. In regard to this matter Duffield[4] says:

"Our most recent knowledge of the motion of the solar atmosphere in the neighborhood of sunspots is primarily due to Evershed, who in 1909 examined the displacement of their spectrum lines with a view to ascertaining the motion of the vapor around their edges. He has made the important discovery that at the low level of the reversing layer there is a motion radial to the axis of the spot. As the level which he examined is without doubt lower than that shown in the spectro-heliograms of hydrogen, there is not necessarily any discrepancy between Evershed's and Hale's discoveries. St. John has made an extended examination of the motion of a number of elements by the same method, and finds that some are moving inward, others outward, while some are stationary. From a knowledge of the vertical distribution of elements in the solar envelope, upon which I have already laid stress, it is possible to draw a vertical section through a sunspot which will show the velocities encountered at different depths.

"The diagram [Fig. 259] represents such a section taken from a paper by St. John.[3] The heavier elements are moving outward along the surface, the velocity falls off as we rise until at a definite level no motion is recorded, and then at higher levels there is an inflow of the vapor of the chromosphere.

"I think we can be sure that associated with this type of motion there is a vertical motion about the spot axis; in St. John's view the main vortex is situated below the level of the diagram, the rotation of charged masses there being responsible for the magnetic field observed in sunspots. The evidence upon which this important conclusion is based is the increase in the magnetic effect when low-level lines are examined."[4]

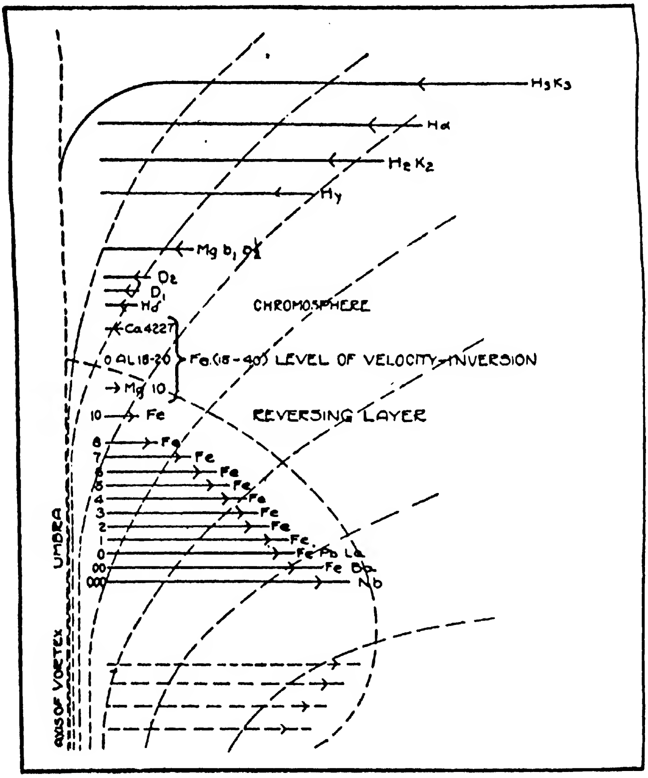
St. John gives three cogent reasons why the descending gases cannot be the counterpart of the outflowing gases beneath them. First, the composition of the material flowing outward in the lower portion is very complex, containing at least twenty-seven elements, while the inflowing material is calcium, hydrogen, magnesium, sodium and probably some of the higher level vapors of iron, aluminium and strontium. Secondly, the mass of the outflowing gases is 276 times that of the inflowing gases. Third,

[3] St. John, C. E.—"Radial Motion in Sunspots," *Astrophysical Journal*, Vol. 37, pp. 322–353.

[4] Duffield, W. G.—*Quarterly Jour. of the Royal Meteor. Soc.*, London, July, 1915, p. 190.

the amount of energy in the outflowing gases, as determined by the mass times the velocity squared, is nearly 2000 times greater in the outflowing air than in the inflowing air above. It is evident from these considerations that the outflowing gases are fed

FIG. 259



Vertical Section Through a Sunspot—After St. Johns

by inflowing gases below them and are probably the top of an immense vortex having more or less the outlines of a dumbbell, so that the nearest terrestrial analogy is a tropical cyclone like that presented in Fig. 21 in which there is an inflow below and an outflow at higher levels. These form a part of the motion

in an immense whirl in which the radial velocity diminishes with increasing height up to a middle plane and then increases in an outward direction; the tangential velocity increases up to the middle plane and then diminishes. Near the center the centrifugal force is so great that rarefaction is produced and the gases at a higher level descend under the influence of gravity into the core of the cyclone. These gases also assume a rotary motion under the influence of the rotation of the sun or earth, but this rotation is independent of that of the primary cyclone and might under certain circumstances have a different direction of rotation.

Faculæ.—Faculæ are areas brighter than the general surface of the sun when seen through a telescope. When photographed in monochromatic light, like that of calcium, they are called flocculi, and are equally visible in all parts of the sun, while faculæ are only clearly visible near the sun's edge. Faculæ are found mainly in the same latitudes as the sunspots, that is, within about 30° of the sun's equator. We are indebted to Deslandres for a knowledge of the motion of the solar vapors in faculæ. By a modification of the spectroheliograph (which he calls a "Velocity Recorder") he has been able to depict the distribution of the velocities with which a chosen material is moving in the various regions of the solar disc, rather than its precise form.

Fig. 260 gives a plot of the movements of the solar vapors in and around faculæ. Examining these with the light of high-level calcium vapor, he finds that within the boundary of a typical facula the material is descending (as the sloping lines indicate), while outside it is rising.

Deslandres suggests that convection currents, resembling those in a mass of water heated from below, are responsible for this motion: a mass of vapor descends in the center, spreads horizontally, rises to its former level, and again descends.

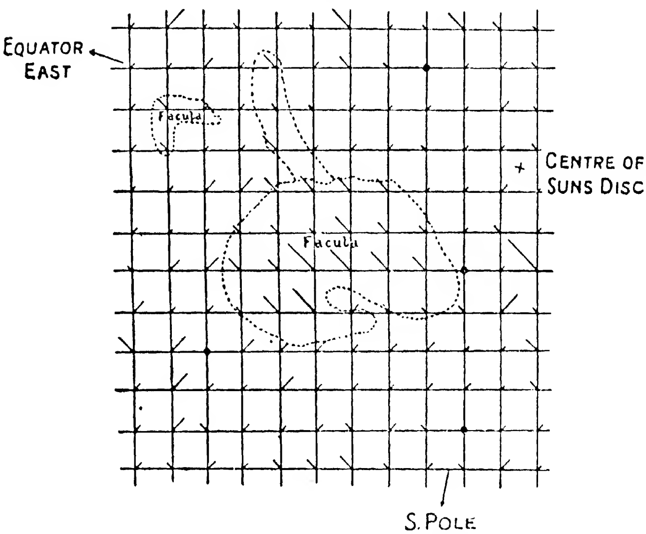
These descending vapors are intimately related in some way to sunspots, but the exact relation remains yet to be determined. If sunspots are immense cyclonic vortices in the photosphere, then perhaps the faculæ are the descending gases which feed in part the outflowing horizontal currents of the cyclone. At times, however, the descending gases appear to be descending directly into the vortex of the sunspot. The great brilliancy of the faculæ is probably due to the heating of the descending gases by compression.

That faculæ are hotter than the surrounding regions is indicated by observations at Mount Wilson.

In the annual report of the Director of the Mount Wilson Observatory, 1921, Dr. Hale says:

"On the Bohr theory of atomic structure, radiation of the normal type occurs only when an electron falls from one orbit to another of lower potential energy. The ordinary enhanced lines of an element are thought to be produced when the atom is

FIG. 260



Distribution of Vertical Velocities in Faculæ—After Deslandres

ionized, that is, when one electron has been removed completely. Saha has developed an expression for the relative proportion of ionized to un-ionized atoms as a function of temperature and decrease of pressure. For elements whose ionization potentials are known, he deduces the state of ionization in the solar atmosphere for assumed values of the temperature and pressure. He suggests that over the faculæ, which are considered to be regions at temperatures higher than that of the photosphere, the spectrum, owing to the increased temperature, should become similar to the spectrum of a star at a temperature higher than that of the sun. This would be shown by an increase in the intensity of the enhanced lines, proportional to the increase in the number of ionized nuclei. Some preliminary spectrograms

of faculæ obtained by Mr. St. John show changes in the intensity of the enhanced lines in agreement with these deductions."

PROMINENCES

Prominences appear to arise from tremendous explosions in the sun's mass due to chemical or mechanical causes as a result of which heated gases are projected outward from the sun's surface with great velocities and to great heights. These gases float like clouds in the outer atmosphere of the sun for a while and then slowly disappear (see Plate XIV). Deslandres' observations have led him to believe that vortical motions around horizontal axes are frequently produced in these ascending columns, resembling the vortical motions sometimes seen in the ascending columns of smoke or steam from a locomotive, but on a grander scale. Prominences are not confined to any particular latitude, but are found all over the sun's surface.

The gases which form the prominences are probably intensely hot when they start on their journey outward from the interior of the sun, but in rising the gases cool by expansion and become cooler than the gases below; so that, when projected on the brighter gases below, they appear like dark bands floating above the solar surface. This effect is clearly seen in the spectroheliograms of hydrogen, (see Plate XV).

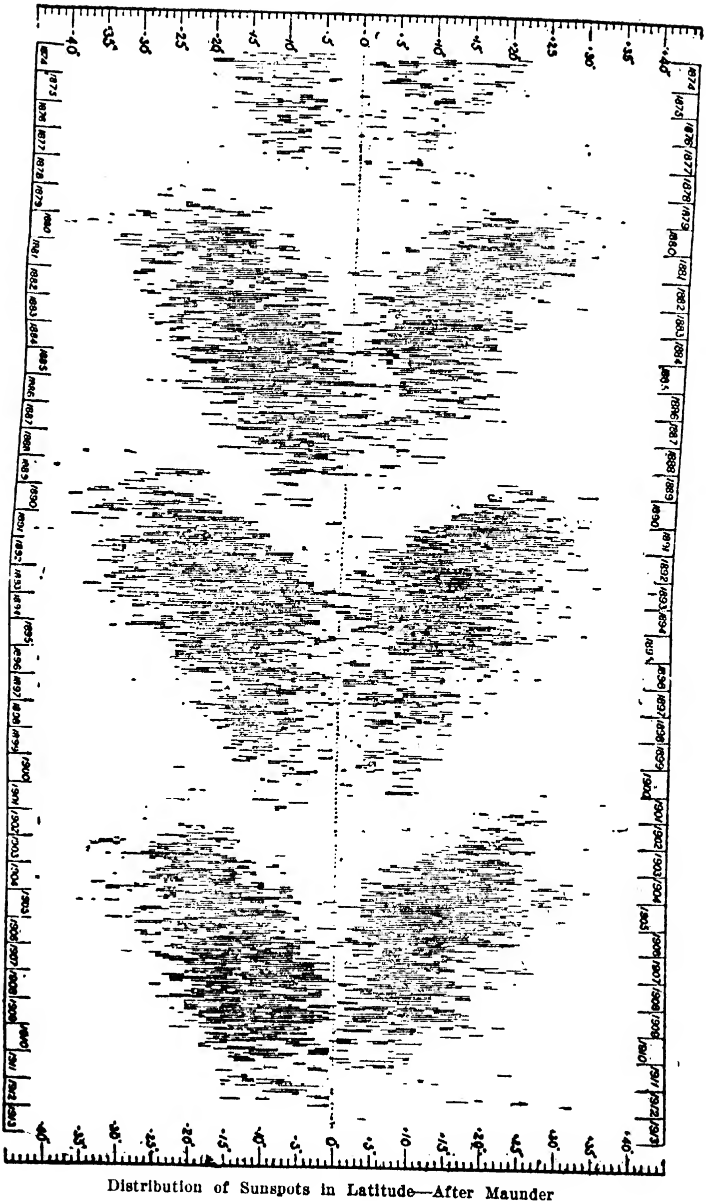
CIRCULATION IN THE SUN'S ATMOSPHERE

That there are systematic movements on a large scale in the sun's mass is evident from the slow changes in the latitude of sunspots in a period of about eleven years.

Fig. 261 shows the position of the sunspots in latitude for each year from 1874 to 1913 according to Maunder. The central or zero line is the solar equator and the degrees of latitude north and south of the equator are shown at the top of the diagram. The dashes in the body of the diagram show the position of the sunspots. It is seen that new sunspots begin about latitude 30° immediately after the years of minimum sunspots, 1878, 1889 and 1901, and the succeeding spots approach the equator until the next year of minimum. At the time of maximum spots they have an average latitude on each side of the equator of about 15°.

Lockyer believed that the prominences have an opposite movement. Showing a maximum frequency at about latitude 40° at

FIG. 261



Distribution of Sunspots in Latitude—After Maunder

the time of sunspot minimum, the area of greatest frequency progresses poleward until the time of the next minimum.

In regard to a general circulation in the solar atmosphere resembling that of the earth Duffield[5] says:

"In terrestrial meteorology the two predominating influences are the rotation of the earth and the excessive heating of the equatorial regions, but as the latter is absent from the solar economy it is scarcely to be expected that the general circulations upon the earth and the sun can have close resemblances.

"If it could be established that the upper solar atmosphere is in motion from the equatorial toward the polar regions, it is obvious that very remarkable effects would be involved as the winds pass over successive parallels of latitude, since these have been shown to rotate with decreasing angular velocity as higher latitudes are approached. Deslandres quotes a theoretical discussion by Helmholtz in which the polar retardation is regarded as itself responsible for a flow towards polar regions. Conclusive evidence of Northerly or Southerly prevailing winds has not however, been adduced. Slocum looked for it by observing the directions in which the tops of the chromospheric flames are bent, but found no excess in one direction rather than another. Investigating in a similar way the higher levels represented by the tops of prominences, he found no motion sufficiently characteristic to be termed a prevailing wind, though a slightly larger number were bent towards the south in equatorial regions (indicating a slight excess of Northerly winds across the equator), while there was a greater tendency for motion towards them away from the poles in middle heliographic latitudes, and at high latitudes an average tendency in the opposite direction. These results appear to be independent of the heights of the prominences.

"Since out of a total of 4600 prominences examined by Slocum only about one third showed evidence of any motion at all, it is obvious that the currents at high levels are by no means pronounced.

"Evidence for the existence of westerly prevailing winds may be derived from some observations of the solar rotation made by Adams, who noted that the angular velocity of rotation of the lighter elements in the solar atmosphere was greater than that of the heavier ones, as the following table shows:

"The lighter elements are at higher levels than the heavier; consequently we conclude from Adams' work that there is greater velocity in the upper atmosphere which may be interpreted as a prevailing westerly wind in this high level in all latitudes. Doubt has, however, been thrown upon the observations made by Adams by the more recent work of Hubrect and by Plasket and De Lury,

[5] *Loc. cit.*, p. 194.

TABLE XXXIV

ROTATION VELOCITIES OF DIFFERENT ELEMENTS IN THE SUN

Element	*Atomic Weight*	*Angular Velocities* * *Equator*	*Lat. 60°*
Hydrogen	1	15.2°	13.7°
Calcium	40	15.0°	12.5°
Manganese } Iron	55 } 56	14.72°	11.62°
Titanium } Iron	48 } 56	14.65°	11.53°
Lanthanum	139	14.49°	11.35°

* The figures refer to the daily angular rotations.

so we shall have to suspend judgment until further information is forthcoming.

"A search for winds parallel to the solar surface was made by St. John by a different method. He came to the conclusion that the calcium vapor at the upper levels of the reversing layer was not moving with appreciable velocity.

"On the whole, it has not been established that there are more than minor resemblances between the circulation upon the sun and that upon the earth. We shall, however, await with interest further researches in this direction, especially those made with Deslandres velocity-recorder, which seems to provide the most powerful means for attacking this problem."

In a treatise by Evershed,[6] published later than the quotation from Duffield, he states the views of Adams that the chromosphere moves faster than the photosphere and says that his own investigations indicate that the prominences rotate faster than the chromosphere and quotes observations of Campbell which indicate that the corona rotates even faster than the prominences.

In other words, if this is confirmed, the higher that one rises in the solar atmosphere the more rapid the drift of the currents in the direction of rotation, just as is true in the earth's atmosphere outside the tropics.

ELECTRICAL CONDITIONS IN THE SUN'S ATMOSPHERE

That electrical disturbances take place on a grand scale in the solar atmosphere is evident from various lines of evidence and it may be that electrical phenomena play a more important rôle in solar phenomena than they do on the earth.

Condensations of vapor which Simpson has shown to be pro-

[6] Evershed, J.—*Memoirs of the Kodaikanal Observatory,* Vol. I, Part 2, p. 77, Madras, 1917.

ductive of electrical charges in the earth's atmosphere take place on a grand scale in the solar atmosphere. That free electrons exist on a large scale in the solar atmosphere is shown by the enhanced lines in the solar spectrum as explained by Hale, quoted in a previous paragraph. That these free electrons projected from the sun even reach the earth's surface is evident by the auroras and magnetic storms which are felt on the earth immediately following great solar outbursts in certain positions on the solar surface.

That vast quantities of these free electrons are present is also rendered evident by the magnetic effect on light produced by rapidly rotating vapors in the solar atmosphere.

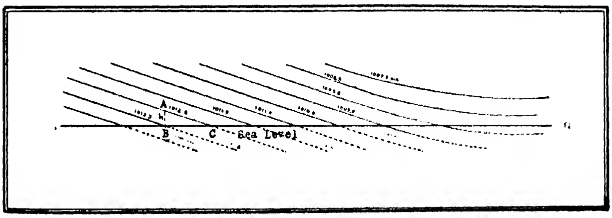
Just how important a rôle these electrical charges play in solar meteorology is yet to be determined, but they are in process of study by means of the enhanced lines and by the banded spectra which characterize vacuum tube or brush discharges of electricity. Ellsworth Huntington believes that these free electrons coming from the sun play a more important part in terrestrial meteorology than has been thought heretofore.

APPENDIX A

FORMULAS FOR COMPUTING PRESSURE GRADIENTS AND WINDS

In computing wind velocity from a pressure gradient there are various factors to be considered. A pressure gradient may be considered as a slope. Fig. 262 shows a vertical section through a pressure gradient with the horizontal scale greatly reduced as compared to the vertical. A particle of air moving from *B* to *C* under a pressure gradient, in case of no friction, would acquire

Fig. 262



Vertical Section Through Pressure Gradient—After W. M. Davis

the same velocity as a particle of air sliding down a frictionless slope *AC*.

The amount of fall per unit distance is determined by the height *h* divided by the distance *BC*, and the acceleration is measured by multiplying the result by the force of gravity which is acting on the particle.

Hence, the gradient force f_p is measured by the formula, $f_p = g\frac{h}{l}$ (1) in which g is the force of gravity, h is the height and l the distance. If the distance within which the gradient is measured is one degree of latitude and the velocity is desired in meters per second, then it is necessary to reduce all measures to meters.

Since the height of an atmosphere of standard pressure and density from top to bottom would have a height of 7991 meters, and the normal pressure at sea level is 1013 millibars, then the height of an air column having a pressure of one millibar would

be 7.8884 meters; so that, in the metric system, when l is taken as one degree of latitude (111,000 m.) the formula becomes:

$$f_p = 9.806 \frac{7.8884\, dp}{111{,}000} \cdot \frac{1013}{p_1} \cdot \frac{T_1}{T_0} = \frac{dp}{387} \cdot \frac{T_1}{p_1} = \frac{dp}{1435} \cdot \frac{\rho_0}{\rho_1} \tag{2}$$

in which p_1 and T_1 are the pressure and absolute temperature (273° + t° C.) at any given place or level and 1013 millibars is normal sea-level pressure. In the last part of the equation the ratio of normal sea-level density to observed density is substituted for pressure and temperature.

When air is set in motion by a gradient force arising from difference of temperature it is acted on by a deflective force (f_r) resulting from the earth's rotation, which according to the formula of Ferrel is,

$$f_r = 2\omega v \sin \varphi + \frac{v^2}{r} \tag{3}$$

In this formula ω is the angular velocity of the earth's rotation, v is the velocity of the wind, φ is the latitude and $\frac{v^2}{r}$ is the square of the wind velocity divided by the radius of curvature of the isobars.

The force f_r is opposed to and balances the gradient force, so that,

$$\frac{dp}{387} \cdot \frac{T_1}{p_1} \sin a = 2\,\omega v \sin \varphi + \frac{v^2}{r} \tag{4}$$

If the air is moving at an angle to the gradient, the sine of the angle (a) must be introduced to make the forces balance. When the air is moving at right angles to the gradient ($a = 90°$), as it will do in case there is no friction, the sine of a becomes unity. The value of ω is obtained by dividing the circumference, 2π, by 86,164 which are the number of seconds in a sidereal day. The value of ω thus obtained is 0.00007292 and $2\omega = 0.0001458$. Substituting this value in the equation and transforming, the value of dp becomes

$$dp = \left(\frac{vp_1}{17.7\, T_1} \sin \varphi + \frac{387 v^2}{r} \cdot \frac{p_1}{T_1}\right) \frac{1}{\sin a} \tag{5}$$

In case the curvature of the isobars is small, the second member of the equation is inappreciable and the formula becomes

$$dp = \frac{vp_1}{17.7\, T_1} \sin \varphi . \frac{1}{\sin a} \tag{6}$$

In such a case the velocity required to balance the gradient becomes,

$$v = \frac{17.7\, dp}{\sin \varphi} \cdot \frac{T_1}{p_1} \cdot \sin a \tag{7}$$

In this case dp is measured in millibars per degree of latitude, T_1 is the temperature on the absolute scale and p_1 the pressure at

the time and place of observation and sin a is the angle of inclination of the wind to the gradient.

Moving air also generates a centrifugal force which tends to lift it from the surface of the earth (see Fig. 28, Chap. I). The diminution of the acceleration of gravity may be computed by the formula,

$$dg = -(2\,\omega\, v \cos\varphi \cos a + \frac{v^2}{R}) \qquad (8)$$

or expressed in differences of pressure,

$$dp = -(2\,\omega\, v \cos\varphi \cos a + \frac{v^2}{R})\frac{p}{g} \qquad (9)$$

in which R is the radius of the earth.

In these formulas g = acceleration of gravity (9.806 m.p.s.) $\omega = \frac{2\pi}{86{,}164} = 0.00007292$, φ = latitude of place, a = angle of wind with meridian, winds moving from west toward east are considered positive and from east toward west negative, v = velocity of wind.

The centrifugal effect is to be considered as additional to the effect computed from the previous formulas (5 to 7).

A stream of air of 50 meters per second in the cirrus level at 42° latitude would lower the pressure only 0.3 millibar as the result of centrifugal force. This difference is too small to produce any appreciable change in the gradients due to temperature but, if acting alone, it could produce an ascending current of about 2000 meters per hour.

Because this force is small it has heretofore been neglected but the full formula for expressing gradient force is,

$$\frac{dp}{387}\cdot\frac{T_1}{p_1}\cdot\sin a = 2\,\omega\, v \sin\varphi + \frac{v^2}{r} + (2\,\omega\, v\cos\varphi\cos a + \frac{v^2}{R})\frac{p}{g}. \qquad (10)$$

In addition there is in every gradient a factor which has not yet been expressed mathematically and that is a vertical component due to difference in density. In equation (4) the density gradient is balanced in a horizontal direction by the forces derived from the deflecting influence of the earth's rotation on moving air; but there remains an unbalanced component in a vertical direction which tends to produce a vertical circulation such as that represented in Fig. 1 showing the circulation produced in a room by a heated stove. This vertical circulation plays an important part in cyclonic circulation and in the general circulation of the atmosphere, because moving air ascending or descending from a level where it is in balance with the pressure gradient carries its velocity with it to the new level. If the pressure gradient at the new level is different from the old, the moving air is no longer in balance. If its velocity is greater than

that needed to balance the new gradient it moves outward against the gradient; but, if its velocity is less than that needed to balance the new gradient it moves inward down the gradient slope. If the air remained at the new level, it would soon be in balance; but where the air is in continuous ascent or descent, however slow it may be, there is a continuous instreaming or outstreaming of air masses which play an important rôle in meteorology.

If the gradients produced by difference in density were in the same direction from the top to the bottom of the air column, the vertical component as well as the horizontal might come into balance with the deflective forces arising from the earth's rotation; but, as the density gradients are in different directions at the bottom and top of air columns of different densities near each other, the total effect on the pressure which is distributed through the air column is neutralized and there remains an unbalanced component in the pressure gradient tending to produce vertical circulation.

APPENDIX B

THE METHOD OF CORRELATION

When the value of anything is stated numerically it is frequently difficult to grasp its relations to the values of other things similarly stated. If, for example, it is said that the price of butter has risen 5 cents and the price of eggs 10 cents no idea is given of the relative changes of the two. But, if it is said that eggs have risen 8 per cent and butter has risen 10 per cent in price the relation is easily grasped. So great is the convenience of comparing changes in this way that the expression of changes in percentages is almost universal. Yet, stated in this way, there is no consideration of the question of time nor of the order of arrangement in space which is vitally important if it is desired to know, whether the two things are intimately related to each other.

Suppose that every time two inches of rain fell over a certain area, a river in that region rose two feet; but, in one case the rise came one day after the rain, in another one week later and in a third two weeks later. Such a condition would not indicate any close association and indeed there might not be any relation whatever.

But if, on the other hand, the river always rose two feet at the same interval of time after the rainfall it would indicate a very close connection.

Suppose that we have a series of numbers which represent inches of rainfall and another series which represent rises of a river in feet on the same day, or at any fixed interval of time afterward, and it is desired to determine the relation between the two. Francis Galton and Karl Pearson have worked out a method of doing this which is known as the method of correlation. The variations are first equally distributed on each side of a mean point or zero. This may be done by arranging the observed values of the two things to be compared in two columns, one of which may be called Column I and the other Column II, then obtaining the mean value for each column and subtracting this mean value from the individual observations for each column separately. That is, the mean of Column I is subtracted from each observed value in Column I and the mean of Column II is subtracted from each observed value in Column II. The two sets of residuals are arranged in columns which we may call

TABLE XXXV

	x	y	x^2	y^2	xy	x	y	x^2	y^2	xy
	10	5	100	25	50	20	10	400	100	200
	8	4	64	16	32	18	9	324	81	162
	6	3	36	9	18	16	8	256	64	128
	4	2	16	4	8	14	7	196	49	98
	2	1	4	1	2	12	6	144	36	72
	0	0	0	0	0	10	5	100	25	50
	−2	−1	4	1	2	8	4	64	16	32
	−4	−2	16	4	8	6	3	36	9	18
	−6	−3	36	9	18	4	2	16	4	8
	−8	−4	64	16	32	2	1	4	1	2
	−10	−5	100	25	50	0	0	0	0	0
Sums	0	0	440	110	220	110	55	1540	385	770
Means	0	0	40	10	20	10	5	140	35	70
						Corrections		10^2 =100	$5^2 = 25$	$10 \times 5 = 50$
						Corrected Means		40	10	20

the x column and the y column as in Table XXXV. Then the method consists in squaring the values in the x column and recording them under x^2 and squaring the values in the y column and recording them under y^2 while the fifth column gives the product of the values in column x by those in column y.

Or else the x values and y values are taken just as observed and corrections applied to the mean values as shown in the second part of Table XXXV. To obtain these corrected values, the mean of the x values is squared and subtracted from the mean of the x^2 values, the mean y values are squared and subtracted from the mean y^2 values and the product of the mean x and mean y values is subtracted from the mean of the xy values. It is seen that the corrected means are the same as the means in the first part of Table XXXV.

To get the correlation between the two sets of values when the sums of x and y are zero, or are corrected as in the second part of Table XXXV, the formula is:

$$r = \frac{\overline{xy}}{\sqrt{\sigma_x \sigma_y}} \qquad (1)$$

From Table XXXV,

$$r = \frac{20}{\sqrt{40 \times 10}} = 1.00$$

In the formula, r is the correlation coefficient, xy is the mean of the product of x and y, σ_y indicates the mean of the x^2 values and σ_y indicates the mean of the y^2 values. These values are the corrected means in the second part of the table. To insure accuracy the means, if not whole numbers, should be carried

to one decimal point farther than the value of the coefficient desired.

In the arrangement shown in the table, r comes out 1.00 because the y values vary exactly in the same way as the x values and in the same time. If, however, the first figure in the y column had been 4 and the second 5 the relation would have come out somewhat less than 1.00. If all the upper figures in column y had been minus and the lower figures plus the relation would have been $r = -1.00$ or an inverse relation, indicating that in proportion as x increased y decreased.

The next question is as to the ratio of the x changes to the y changes. This is found by dividing the mean of xy by the mean of x^2. From the data given in Table XXXV, $\frac{20}{40} = 0.5$, which means that for every change of x the y values change half as much, so that the x values multiplied by 0.5 give the equivalent y values. To determine the ratio of y to x, divide the mean of xy by the mean of y^2 which from the table, $\frac{40}{20} = 2$. That is the y values multiplied by 2 give the equivalent x values. These are designated by b_x and by b_y. The formulas are,

$$b_x = \frac{xy}{\sigma_x} \text{ and } b_y = \frac{xy}{\sigma_y} \tag{2}$$

In determining correlation it is well to plot the values before computation by taking values of x along a horizontal line and y along a vertical line to see if the results tend to fall along a straight line. Otherwise, the correlation method does not hold. If certain values vary as the square of other values, the correlation can be made by taking the square root of the variable which increases as the square, or following a like process for other powers. Thus it may be found that for every rise of ten degrees of temperature above 10° C. (50° F.) in summer the number of flies goes up geometrically. Suppose there are about four times as many for twenty degrees of rise, about nine times as many for 30 degrees of rise, etc. In such a case it would be necessary to take the square root of the number before determining the correlation. In some cases it is necessary to obtain the logarithm of one or both sets of numbers before computing correlations. (For example see Fig. 219.)

As to the meaning of correlation, a high-correlation, coefficient (over 0.50) means a close connection between the two things compared, provided there are a sufficient number of cases, say, 25 or more, but the high correlation does not prove that either one is the cause of the other. For example, the number of flies in a house might show a high correlation with the number of

pleasure yachts in the offing, because both are related to the heat of the summer, but not to each other.

Moreover, a small correlation does not prove that there is no relation between the two things compared. For example, if a main river has two branches both affected by the rainfall over the watershed, but the water of one branch, having a swifter current, flows into the main stream more rapidly than the other, it might happen that the rises and falls of the two streams neutralized each other and that a small correlation or no correlation would be found between the rainfall and the changes of the main stream, although a high correlation was found for each of the branches: but the small correlation would not prove that the changes in the main stream were not produced by the rainfall.

On the other hand, when the number of observations is not large a fairly high value of the correlation may be obtained from merely accidental coincidences. For this reason it is customary to compare the correlation coefficient with its probable error. The probable error of the correlation coefficient is computed by the formula: $e = 0.674 \frac{1-r^2}{\sqrt{n}}$ (3)

When r is 5 times as great as e or more the correlation is considered highly probable. Even when the correlation coefficient is small and the relation not very intimate a correlation coefficient 5 times greater than e is taken as proof of a correlation.

Treated in the right way the method of correlation is extremely valuable in research, because it frees comparison from personal bias and enables the investigator to arrive at definite numerical relations.

In computing the correlation coefficient, various factors are obtained, each one useful for some especial purpose.

These are: (1) The *mean* values of x and y which may be designated x_m and y_m. (2) The means of the squares of x and y which are called the *standard deviations* and are used as a measure of the variability of x and y. These are designated by the symbols σ_x and σ_y and are useful in many classes of statistical work. (3) The *correlation coefficient* which is usually designated r. This is a measure of how closely the changes of x are related to the changes of y in time or space. (4) The relation of the changes of x to those of y or of y to x. These are usually designated by the symbols b_x and b_y and are frequently called *regression factors* after Galton who used them in a study of regression. (5) The *probable error* of the computed values of r is designated by e and is useful not only for establishing the probability of a relation between the two quantities, but also in other mathematical processes. (6) The relation of e to r, sometimes called the *correlation ratio.*

When the mean values are not whole numbers as in Table

XXXV, it is necessary to use so many decimals in the mean results to insure accuracy that it is frequently better to use the sums instead of the means in the computations. When the means of x and y are zero, as in the first part of Table XXXV, the formula for the correlation coefficient is,

$$r = \frac{\Sigma xy}{\sqrt{\Sigma x^2 . \Sigma y^2}} \tag{4}$$

From Table XXXV,

$$r = \frac{220}{\sqrt{440 \times 110}} = 1.00$$

But, when the means of x and y are not zero as in the second part of Table XXXV, then,

$$r = \frac{(n\Sigma xy - \Sigma x . \Sigma y)}{\sqrt{(n\Sigma x^2 - (\Sigma x)^2)\ (n\Sigma y^2 - (\Sigma y)^2)}} \tag{5}$$

When b_x and b_y are computed from the sums, if the sums of x and of y are zero, as in the first part of Table XXXV, the formulas are:

$$b_x = \frac{\Sigma xy}{\Sigma x^2} \text{ and } b_y = \frac{\Sigma xy}{\Sigma y^2} \tag{6}$$

But, if not zero as in the second part of Table XXXV, then the formulas are:

$$b_x = \frac{n\Sigma xy - \Sigma x . \Sigma y}{n\Sigma x^2 - (\Sigma x)^2} \text{ and } b_y = \frac{n\Sigma xy - \Sigma x . \Sigma y}{n\Sigma y^2 - (\Sigma y)^2} \tag{7}$$

From the values in Table XXXV, the results are:

$$b_x = \frac{11\ (770) - 110 \times 55}{11\ (1540) - 110 \times 110} \text{ and } b_y = \frac{11\ (770) - 110 \times 55}{11\ (385) - 55 \times 55}$$

When x and y are large numbers it is advantageous to subtract the minimum observed value from all the values before beginning the computations or else subtract some even number like 100, 200, or 1000.

At times the amount of work can be lessened, without greatly decreasing the accuracy, by dividing all the numbers by 3, 5, or 10.

In the case considered in Table XXXV the values of y varied at the same time and in the same way as the values x, but such a case is rarely found in nature. Usually natural things like the number of flies in summer or the amount of corn produced per acre are affected by more than one independent variable.

In the example given in Table XXXV, suppose that y is affected by the changes of x and also by changes of another kind or by a series of other changes which we can call z. The correlation of x with y will no longer be 1.00 but a much small number. If there are enough observations, however, the relation of x to y can be separated from the influence of z by means of averages.

Because if z is independent of x its effect will be sometimes to increase the apparent effect of x and at other times to decrease it, so that by averaging a large number of values of y corresponding to the same value of x the increases and decreases produced by z neutralize each other and the mean value of y gives its relation to x. Thus in Table XXXVI there are supposed to be observed ten values of y corresponding to successive values of x from $+10$ to -10, in steps of 2. Since, the effect of x is constant in each column the fluctuation in y in that column must be due to z. But as the influence of z is eliminated, or approximately eliminated by the averages, the mean values of y show the variations due to x.

It is further possible to determine the error of the mean value and how many observations are necessary for its exact determination by getting average deviations of the y values from their mean value in each column and dividing this average by $\sqrt{n}$, the n being the number of values in each column. The average deviation for Column I in Table XXXVI is 0.54 and the probable error of the mean (5) is 0.51 unit.

TABLE XXXVI

Values of x..	10	8	6	4	2	0	−2	−4	−6	−8	−10
Values of y.	4	3	2	0	1	−2	4	−2	−4	−3	−5
	2	1	5	4	−1	4	2	−6	−3	0	−4
	7	8	3	−2	0	2	0	−1	−2	−7	−6
	9	4	7	4	2	−4	−2	0	−6	−5	−8
	4	2	1	6	4	1	−4	−2	−2	−2	−4
	8	7	2	1	−4	−2	3	2	−3	−7	−7
	5	4	0	0	3	0	−6	−2	0	−4	−5
	2	5	6	2	2	4	−2	−1	−5	−6	−3
	5	6	3	4	1	−4	−2	−6	−2	−4	−4
	4	0	1	1	2	1	−3	−2	−3	−2	−4
Sums........	50	40	30	20	10	00	−10	−20	−30	−40	−50
Means.......	5	4	3	2	1	0	−1	−2	−3	−4	−5

If the correlation of x and y be computed from the individual observations in Table XXXVI, there are 110 different values and the correlation comes out $r = 0.82$. This correlation, although high, is not as useful for prediction as might at first be anticipated because it is impossible to tell in advance how the other unknown variable z is going to behave. Its influence on y may increase greatly in the future and completely obscure x.

But by determining the relation of x to y from the means, it is possible to determine to a high degree of accuracy the relation of x and y by means of the b_x and b_y values.

The correlation between x and the mean value of y in Table XXXVI is 1.00 and $b_x = 0.5$ as in Table XXXV, but in Table

XXXVI the mean values are made exactly equal to the values of y in Table XXXV, while in Nature this would rarely occur except in case of a large number of observations.

A better test is obtained by inverting the table and getting the values of x in terms of y. This was done by making a table like Table XXXVI in which the values of y were arranged in order at the top and the corresponding values of x placed in columns below. Thus for each value of $5y$ there were values of $10x$ twice, $8x$ once and $6x$ once, and so on for each successive value.

The means are shown in the following table:

TABLE XXXVII

Values of y....	5	4	3	2	1	0	−1	−2	−3	−4	−5
Mean values of x	8.5	4.8	4.0	3.7	3.6	0.0	1.0	3.5	−6.9	−5.5	−8.0

From the values in Table XXXVII the correlation coefficient comes out 0.97 and the b_y value equals 1.6. The correlation between the individual values may be called the correlation of the first order and that between the means may be called the correlation of the second order. It is seen from these results that correlations of the second order are a much greater approximation to the true relation than correlations of the first order.

Had there been five times as many values of y, the approximation would have been closer and perhaps exact.

For determining the influence of other variables on y, it is best to eliminate the influence of x by computing the values of y from the b_x ratio and working with the residuals, or if y is not a linear function of x by subtracting the mean values of x as obtained in Table XXXVI, and treating the residuals for the other variables in the same manner as for x shown in Table XXXVI.

Yule in his treatise on "An Introduction to the Theory of Statistics," pp. 229-252, gives formulas for determining the second order of correlation of two variables when the first order of each to a third variable is known which he calls the method of partial correlation. These formulas assume, however, that all the variables are straight-line functions which is rarely the case in nature. The method of eliminating the effect of the other variables, whether one or many, by means of averages as shown in Table XXXVI does not assume anything in regard to the character of the other variables except that their mean effect when taken at random is zero.

G. F. McEwen has worked out a better method of separating the variables by a process of grouping and by successive approximations and the results are published in the *Proceedings of the American Academy of Science*, Vol. 55, No. 2, December, 1919.

For further information on this subject the reader is referred to these two authors.

In commenting on the meaning of correlations of the first order (derived from comparing individual observations with each other), Mr. W. H. Dines writes in the "Computers' Handbook," Section V, London, 1915:

"Like all other statistical quantities, a correlation coefficient is subject to error and its standard error is equal to $\frac{1-r^2}{\sqrt{n}}$ but this formula itself is not valid if n is too small. Suppose that $r = .50$, a fairly high value, and $n = 25$ then the standard error is $\pm .15$. To be quite certain that the result is not a chance one, a value equal to some four times the standard error is necessary so that a coefficient of .50 on 25 observations need not be significant."

He remarks further:

"It is apparent too that if the coefficient is very high fewer observations are necessary to establish it since $1-r^2$ is then small. Let σ_1 be the standard deviation of a certain quantity which is denoted by the suffix 1. If a person knowing only the mean value were asked to make a guess at the value of this quantity on a definite occasion, he would make the best guess possible by quoting a value close to the mean, but he might be as much as $4\sigma_1$ out, and most probably he would be as much as $2/3\sigma_1$ out. If he knew the value of another quantity, suffix 2, on that occasion and the correlation r_{12} between the two quantities, he could make a better guess. Its standard error σ_2 would be reduced in the ratio of $\sqrt{1-r^2}$: 1 since it has been proved that:

If $r = .60$ this ratio becomes .8, for $r = .80$ the ratio is .6, while as high a value as $\sqrt{.75}$, or .87, is required to make the ratio .5, that is to halve the estimate. Looked at from this point of view, small differences in the value of a correlation coefficient are of no consequence whatever while that coefficient is small, but become important only when it is large. Thus it matters little if $r = .30$ or if $r = .40$, but it makes a great difference if $r = .95$ instead of .90."

These remarks might also be extended to cover the computed values of b_x and b_y when the correlation coefficient is small and they show the necessity in such cases of eliminating the other variables by means of the method of averages illustrated in Table XXXVI and of determining values for as many variables as possible before using the results for predictions.

When the primary correlation between two quantities is small, but is a true correlation, as shown by its relation to the probable error (Σ), or by its persistence in different samples or in different divisions in time, it is an indication that there are more than one variable in the quantities compared and that there is a correlation between one set of variables, but not between the others.

Thus, it has been shown that there is a correlation between the marriage rate in Great Britain and economic conditions, as for example the values of exports and imports per capita. Exports and imports per capita show a progressive increase not shown by the marriage rate, but when plots of the two are examined, it is seen that there are oscillations in the marriage rate of about nine years and also similar oscillations in exports and imports.[1] The correlation between the two is in these shorter oscillations and not in the long drift. In such cases the shorter oscillations can be separated from the longer drift or from longer oscillations by means of progressive averages of about the length of the shorter oscillations. Thus successive means of the exports and imports per capita for nine years show a smooth curve of long period which when subtracted from the observed values leave the smaller oscillations as residuals. Between these shorter oscillations and the marriage rate there was found a high degree of correlation.

Hence, it is well to separate any curve indicating variables of different length into two or more classes of variables by means of numerical smoothing when seeking unknown correlations.

[1] Yule—*An Introduction to the Theory of Statistics*, p. 199.

APPENDIX C

HARMONIC ANALYSIS

If there is any reason for believing that conditions tend to repeat themselves in any regular order, or after the completion of the same interval of time, they may be considered as progressing around a circle and the conditions are thought of as moving in cycles or periods.

When these periods are divided into equal parts and the conditions are measured and expressed numerically for each of these equidistant positions or equidistant intervals of time, then, by means of the formulas of harmonic analysis, the data may be obtained for drawing a smooth curve through the observed values. This curve may be in the form either of a circle or of a sine curve. See Figures 129 and 130.

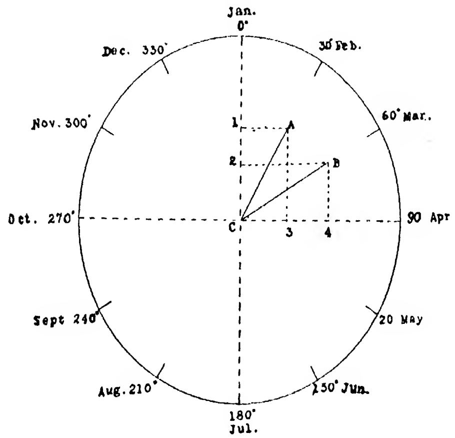
The most marked periods or cycles in meteorology are the daily period caused by the rotation of the earth on its axis, and the yearly period, caused by the movement of the earth around the sun. Each of these movements brings about rhythmical changes in the amount and intensity of sunshine received at any place and these changes cause the daily and yearly periods in the conditions of the atmosphere.

The simplest conception of harmonic analysis is that the observed values in any cycle occur at equal distances around a circle and that all the observed values may be resolved into components, the resultant of which divided by the proper factor gives the radius of a circle running through the observed values.

Suppose, for example, that the annual period of temperature is under consideration and the mean of the observed temperatures has been obtained for each month; then the year may be considered as a circle divided into twelve parts and, if plotted on a circle of 360°, each month would be 30° from the preceding one, so that the twelve months would complete the cycle. In Fig. 263 let January represent the beginning of the year, then February will be at 30°, March at 60°, etc. The object of the analysis is to reduce the mean observed values to components in two different directions, namely, $C0$ and $C90$. The mean observed values for January, April, July and October would lie along these lines; but the values for the other months would lie between these two directions. If in Fig. 263 the mean of the

observations for February is represented by the line AC, then the component in the direction $C90°$ is obtained by multiplying the mean of the observed value by the sine of 30° and its plotted value is $C3 = A1$. The component in the direction $C0$ is obtained by multiplying the observed mean by the cosine of 30° the plotted value of which is $C1 = A3$. The components of the value CB are obtained in the same way and are $C4$ and $C2$. The components of the succeeding months are obtained in a like manner by multiplying the means of the observed values by the sines and cosines of 90°, 120°, 150°, etc., to 330°. The sum of all the sine

Fig. 263



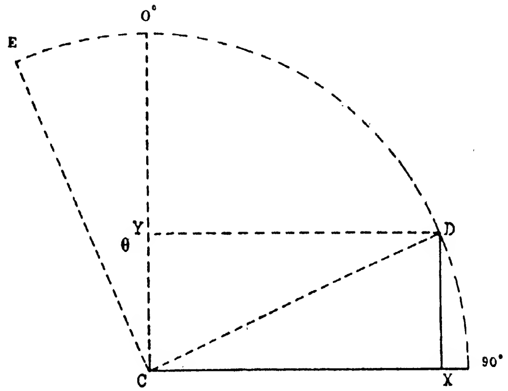
Resolution into Rectangular Cordinates by Harmonic Analysis

values will give the components in the direction $C90$ and the sum of all the cosine values will give the component in the direction $C0$. The sine and cosine values on one side of C are positive and on the other side negative, hence any constant or mean value running through the whole of the observations will cancel in the process of summing the results and only the excess in one direction or other will remain.

If CX in Fig. 264 represents the sum of the sine terms and CY the sum of the cosine terms, then the mean resultant CD is obtained from the well known formula for getting the hypothenuse of a triangle, $(CD)^2 = (CX)^2 + (CY)^2$. The value CD divided by one half the number of parts into which the circle is divided represents the amplitude of the period, usually designated by the symbol a. The position of the point D on the circle

is determined by the angle DCO which is obtained by dividing CX by $CY = \frac{\Sigma \text{ sine terms}}{\Sigma \text{ cosine terms}} = \tan DCO$. Usually in harmonic analysis it is desired to obtain not only the maximum value, but the point of beginning of the cycle where the value is zero. The maximum D is 90 in advance of that point, which is at the point E, and the distance OE on the circle is determined

FIG. 264



by the angle 0 which is the complement of the angle CDO and, hence, is equal to the angle DCX and the $\frac{\Sigma \text{ cosine terms}}{\Sigma \text{ sine terms}} = \text{Cot.}$ $DCO = \tan 0$.

Expressed mathematically: let $l_0, l_1, l_2 \ldots l_{n-1}$ be observed values which are associated with equidistant values of some argument, say time; then the single periodic terms, namely, coefficients of a sine curve passing through the observations, may be represented by the trigonometrical formulas:

$$L = A_0 + A_1 \cos \varphi + B_1 \sin \varphi \quad (1)$$

in which

$$A_0 = \frac{\Sigma l}{n}, \ (2) \qquad A_1 = \frac{\Sigma l \cos \varphi}{\frac{1}{2} n}, \ (3) \qquad B_1 = \frac{\Sigma l \sin \varphi}{\frac{1}{2} n} \ (4)$$

$$\frac{A_1}{B_1} = \tan \theta, \ (5) \qquad a = \sqrt{A_1^2 + B_1^2}, \text{ or } a = \frac{A_1}{\sin \theta}, \ (6)$$

$$\varphi = \frac{360°}{n}. \ (7)$$

0 = angle of epoch, namely, the angular distance from zero to the part of the sine curve at the time of the first observation. The quadrant of 0 is determined by the signs of A_1 and B_1, being

in the first quadrant when the signs are +/+ in the second when they are +/—, in the third when they are —/—, and in the fourth when they are —/+; a = amplitude.

Example.—Where n = 12 (it might be 12 observations at intervals of two hours, or 12 observations at intervals of one month, or 12 observations at intervals of one year).

$$A_0 = \tfrac{1}{12} \sum_{r=0}^{r=11} I_r \quad (8) \qquad A_1 = \tfrac{1}{6} \sum_0^{11} I_r \cos \varphi \quad (9)$$

$$B_1 = \tfrac{1}{6} \sum_0^{11} I_r \sin \varphi \quad (10)$$

in which I_r is equal to successive values of I from 0 to n–1 and θ_r successive values of θ from 0 to n–1.

By assigning various values to r, period of any length may be computed.

Examples of the computations made in cases in which there were eight, nine and twelve terms are given in Table XXXVIII. It is seen that in the cases of eight and twelve terms it is necessary to multiply only half of the number of terms by the sine and cosine factors, because after 180 the sines and cosines simply repeat those in the first half of the circle, but with opposite signs. Hence, multiplying the differences between the two halves by the sines and cosines and summing gives the same values as if each term had been multiplied by its proper sine and cosine factor and summed together. In the case of odd terms like 9, it is necessary to multiply each term by its corresponding sine and cosine factor before adding. It will be noticed that only one decimal has been used in the sines and cosines. Where great accuracy is required two or more are necessary.

The subdivisions of the period may be for any intervals, hours, days, weeks, months or years, depending on the length of the period. In cases where extreme accuracy is desired the period is divided into an infinite number of intervals and integrated by the formulas of calculus.

HIDDEN PERIODICITIES

Marked periodicity in any element can usually be detected by plotting the observed values. The eye can then detect from the more or less regular oscillations the existence of any marked periodicity which may exist in the values. But in case there are a number of nearly equal periods summed together a plot of their variations gives an irregular curve in which no periodicity can be detected. The same is true if a periodicity of small amplitude is mixed with a number of irregular variations. In case the length of the individual periods are known they can be separated from each other or from irregular variations by dividing the time into intervals of the length of any selected period

TABLE XXXVIII

EXAMPLES OF COMPUTATION OF PHASE ANGLES AND AMPLITUDES IN PERIODS OF 8, 9, AND 12 TERMS, OR DIVISIONS

8 DIVISIONS

T (1)	T (2)	Diff.	Sin values	Cos values	Products Sin	Products Cos
1.9	7.2	— 5.3	0.0	1.0	0.00	— 5.30
4.0	6.0	— 2.0	0.7	0.7	— 1.40	— 1.40
4.0	1.9	2.1	1.0	0.0	2.10	0.00
9.2	0.1	9.1	0.7	— 0.7	6.37	**— 6.37**
Sums					+ 7.07	**— 13.07**

$\theta = 298$ a = 3.71

9 DIVISIONS

T	Sin values	Cos values	Products Sin	Products Cos
1.9	0.0	1.0	0.00	1.90
4.0	0.6	0.8	2.40	3.20
4.0	1.0	0.2	4.00	0.80
9.2	0.9	— 0.5	8.28	4.60
7.2	0.3	— 0.9	2.16	— 6.48
6.0	**— 0.3**	— 0.9	— 1.80	5.40
1.9	— 1.0	— 0.5	— 1.90	- 0.95
0.1	— 0.9	0.2	**— 0.09**	0.02
2.3	— 0.6	0.8	— 1.38	1.84
Sums			+ 11.67	— 9.67

$\theta = 320$ a = 3.37

12 DIVISIONS

T (1)	T (2)	Diff.	Sin values	Cos values	Products Sin	Products Cos
— 0.9	2.3	— 3.2	0.0	1.0	0.00	— 3.20
1.7	1.7	0.0	0.5	0.9	0.00	0.00
1.5	2.3	— 0.8	0.9	0.5	— 0.72	— 0.40
2.3	6.0	— 3.7	1.0	0.0	— 3.70	0.00
— 0.1	3.7	— 3.8	0.9	— 0.5	— 3.42	1.90
0.9	**— 8.5**	4.4	0.5	— 0.9	2.20	— 3.96
Sums					— 5.64	— 5.64

$\theta = 225$ a = 1.32

T = observed temperatures

and getting averages for each term of the period after a great many repetitions of the period. Thus the annual period in rainfall is separated from irregular variations by getting means for each month for a great number of years.

Balfour Stewart suggested that in the case of hidden periodicities where the length of the period was unknown, the period might be detected by taking trial periods of different lengths, dividing them into equidistant intervals and then getting averages of the different terms of each period after a great many repetitions of the period. The plus and minus values of the irregular non-periodic changes tend to neutralize each other; while any true period shows itself by a greater range than that of the trial periods in which there is no periodic term. In the case of the true period the values in the same part of the period do not neutralize each other but steadily increase the totals with additional repetitions. The true periods would hence disclose themselves by showing a greater amplitude than other trial periods.

Prof. A. Schuster improved on this method by introducing harmonic analysis and computing the amplitude of each trial period from the average of numerous periods. A plot of the amplitudes of trial periods of successively greater length was called a *periodogram.* Professor Schuster computed the prob-

ability or expectation of any given deviation of amplitude from the general level. His calculations showed that in case the amplitude of any trial period was from three to five times greater than the mean of all the amplitudes, the probability of its being a true period was many thousands to one.

There are periodic or semiperiodic changes, however, like the return of sunspots to the same position on the sun as seen from the earth which cannot be treated in the manner suggested by Schuster. Turner studied the sunspot period by analyzing successive individual periods, but a more detailed process was devised by the author in the study of the semiperiodic changes in solar radiation and their possible connection with solar rotation or other variables of a similar nature.

If periods of different lengths are tried of nearly the length of some known period, as for example that of the daily period in temperature, and the values of θ and a are computed for successive individual periods, say for 22, 23, 24, and 25 hours, it will be found that when the computed values of θ are plotted on a diagram like 8, Fig. 265, the trial period is longer than the true period, the successive values of θ fall along a line diverging from a horizontal line and beneath it as *AC*. When the trial period is identical with the true period, the dots fall along a horizontal line showing no change in θ; but when the trial period is shorter than the true period, the values fall along a line rising above the horizontal as *AB*. To compute the length of the true period it is necessary to project the line until it crosses 360°.

Thus, supposing *AB* to have been calculated for a period of 26 hours when the true period is 24 hours, it would cross the plot from 0 to 360 in 12 periods. Since this crossing is equivalent to the loss of one period there must have been 13 repetitions of the true period; hence $\frac{26 \times 12}{13} = 24$, or expressed mathematically,

$$p = \frac{p'n}{n+1} \tag{11}$$

but when the trial period is shorter than the true period the formula becomes,

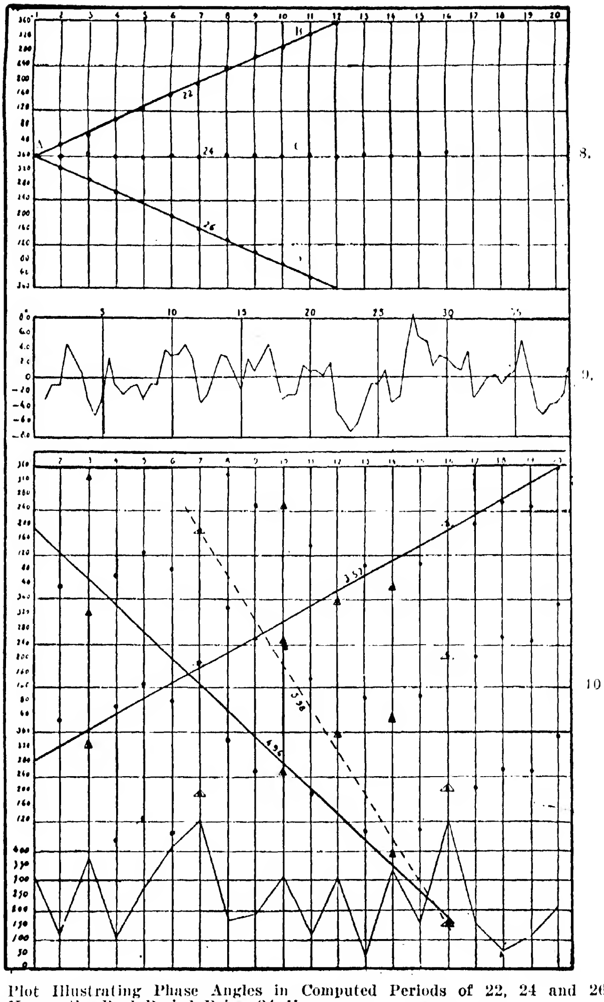
$$p = \frac{p'n}{n-1} \tag{12}$$

in which n is counted in periods and fractions of a period, p is the true period and p' is the trial period. In such a case a plot of the amplitude a is nearly a horizontal line.

A test of the formulas was made by combining a number of different periods. Assuming certain phase angles and amplitudes for ten periods of different lengths and amplitudes values were computed for half-day intervals by the formula,

$$I_r = A + a \sin \varphi, \tag{13}$$

FIG. 265



8. Plot Illustrating Phase Angles in Computed Periods of 22, 24 and 26 Hours, the Real Period Being 24 Hours.
9. Curve Formed from Combination of 10 Periods of Different Lengths and Amplitudes.
10. Harmonic Analysis of Data Plotted in Curve, Fig. 9, Using Trial Period of 4 Days.

in which l_r are successive computed values of l corresponding to successive values of θ at half day intervals. The terms l_r and θ_r remain as previously defined. No. 9 in Fig. 266 shows a plot from the sum of the computed values of the periods selected. The computation was extended to an interval of 80 days. The plot covers only a portion of this interval.

Table XXXVIII shows examples of the computations where r equaled 8, 9, and 12 half days. A plot of the computed values of θ and of a for the period of four days (8 half days) is given in No. 10, Fig. 266. The ordinates are in degrees and are repeated three times from 0 to 360, while the abscissas are successive periods. The values of θ are shown by dots. Small triangles indicate the values of θ corresponding with maxima in the amplitudes; larger triangles indicate the largest amplitudes. At the bottom of No. 10 is given a plot of the amplitudes for 20 successive periods of four days. The plot of the successive values of θ may be called a *phasogram* and of a an *ampligram* as functions of the time (T). Plots of this kind were made for each trial period. The lengths of the trial periods are seen in Table XXXIX. It is seen that the plot of the amplitudes in No. 10 shows irregular variations. The interpretation of this is that the maxima indicate times when the phases of two or more periods come together. The secondary maxima were interpreted as indicating that two periods were beating together, that is, were in the same phase, while the larger maxima indicate that three or more periods were near the same phase. With these points in mind the following rules were drawn up for determining the true periods from the plots.

(1) Mark the epoch angles on the plot by some especial symbol where the amplitudes show maxima. In the plot No. 10 these points are indicated by triangles.

(2) Whenever a number of triangles on the plot appear to lie in a straight line, draw lines through them (see line marked 3.57 in 10).

(3) These lines should pass through or near the points where the epoch angles coincide with maximum amplitudes or beats (indicated by the triangles in the plot). Two lines at different angles to the horizontal should pass through or near the triangles coinciding with secondary maxima in the amplitudes and three or more through or near the triangles corresponding with the larger maxima.

(4) When a line drawn through the triangles slopes downward from the point of beginning the true period p is shorter than the trial period p'. When it slopes upward the true period is longer than the trial period. For computing the length of the true period from the slopes of the lines, formulas (11) and (12) previously given are used.

(5) To obtain the true epoch angle 0, at any time, read the angle indicated by abscissas cutting the line at the selected point of time and correct the reading by the formula,

$$\theta = \theta' + \frac{360}{p} \cdot \frac{p - p'}{2} \qquad (14)$$

The correction is plus when the line slopes upward and minus when it slopes downward.

The results obtained by this method of harmonic analysis of the data shown in 9, Fig. 265, are given in Table XXXIX.

The first two columns in the table show the length in days and fractions and the second the amplitude of the periods from the summation of which curve 9 in Fig. 265 was constructed. This curve, though drawn from the summation of only ten harmonic periods, appears to be absolutely fortuitous, yet the analysis of the data by a person who did not know the number or length of the periods from which it was constructed gave the results shown in the table. How these results were obtained from each trial period may be understood by noting the results in the column headed 4 and comparing these with the computed periods shown by the numbers along the line in 10, Fig. 265. The last column giving the mean shows how close an approximation was obtained to the length of the true periods. After the length of the periods are found the amplitudes are obtained by averaging the data in periods of the length of those found and computing the amplitudes by harmonic analysis.

TABLE XXXIX

Periods Derived from Harmonic Analysis of Trial Periods

True Periods		Length of trial periods in days at top of columns, estimated true periods below										
Days	Amp.	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	Mean
1.00	0.5	1.19	1.17									1.18
1.44	1.0	1.43	1.41									1.42
2.00	1.3	1.99	2.00	1.99	2.00							2.00
2.77	1.5		2.89	2.76	2.77	2.73						2.79
3.60	2.0			3.56	3.61	3.60	3.57	3.62	3.67	3.54		3.60
4.80	1.0					4.46	4.96	4.42	4.83		4.42	....
6.10	1.2				6.09	5.91	5.98	5.79	6.30	6.21	6.09	....
8.55	1.5									9.17	8.40	....
Days	Amp.	7	8	9	10	11	12	14	16	18	20	Mean
4.80	1.0	4.98										4.68
6.10	1.2	6.32	5.81	6.91	6.49							6.17
8.55	1.5	8.55	8.92	8.49		8.63						8.60
12.00	1.2			12.14	10.64		11.91	12.54				11.81
18.00	2.0		18.53		16.63	17.63	17.91	17.84	18.70	18.00	19.22	18.06

This method makes it possible to separate and study periodic changes of short duration such as might result from solar outbursts in particular regions of the sun which lasted for a few rotations and then disappeared.

HARMONIC ANALYSIS IN IRREGULAR OR NON-PERIODIC CHANGES

In the preceding cases single harmonic periods represented by simple sine curves (Fig. 130) have been considered. If, however, any observed data covering any given interval of time is subdivided into a great many different periods the length of which are submultiples of the time interval, as, for example, one, one half, one third, one fourth, etc., and the harmonic values of the main period and of all the submultiples are computed (Fourier series), the observed data, however irregular, may be represented by the summation of all the computed periods. This method of representing observed data has many useful applications, but does not imply the existence of any cycles or periodic changes.

It was also shown in Chapter IV that harmonic analysis may be used to separate from each other and study wave-like changes which are not necessarily periodic but only of different lengths from crest to crest (see Fig. 131).

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